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A MODEL OF ANTIFRATRICIDE SHIELD INTERACTION WITH JETS FORMED BY MULTIPLE ARTILLERY ROUND DETONATIONS

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US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
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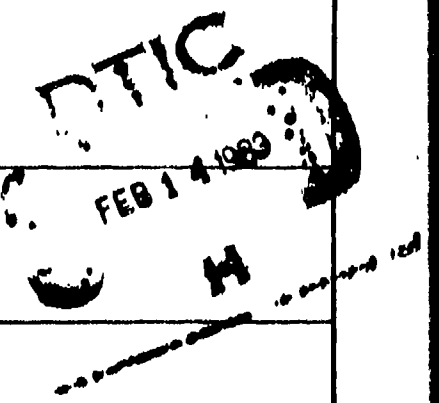

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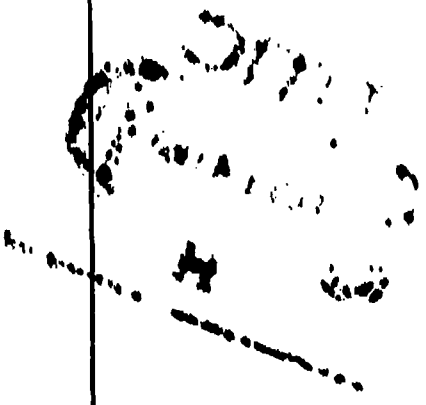
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) (kjm)

This report presents a theoretical model of certain influence attenuation effects involved in round to round detonation propagation. The purpose of the model is to provide guidance in the design of structures to safely store and transport HE filled munitions. Such structures employing isolation panels or shields between artillery shells or groups of artillery shells are to prevent the propagation of detonations in the event that one or several shells are detonated by other means. The most severe effect to be shielded against is the

metal jetting produced when neighboring shells are simultaneously detonated. The present report deals with the interaction that occurs between such metal jets and multi-layered shields composed of inert materials, explosive layers, or semiactive (hydrated) materials that derive their energy from the kinetic energy of the impacting metal jet and shell casing fragments. The study finds that the model correctly reproduces most features found in experiments with isolation panels, that present semiactive materials such as gypsum show only minor enhancement of shield performance, and that the use of proper positioning of panels and distribution of shield material is a significant parameter for the design of such structures.



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I. INTRODUCTION

This report deals with the problem of optimizing the packaging for artillery shells to provide protection against influence initiation in the metal jetting environment produced by shell casing impacts. The initiation of a shell stored or transported with other shells produces high speed casing fragments that on impact with nearby shells can cause shocks, penetration, and/or fracture resulting in the initiation of the explosive fill in the neighboring shells. In addition, the detonation of two adjoining shells can, as their casings impact, produce significant metal jetting. In the case of 155 mm artillery shells this metal jet can cut through as much as 15 cm of steel. As such, this latter mechanism represents the most severe fratricide environment constraining shield design. Neighboring shells can be protected from this jet of material by inserting layers of material to intercept and disrupt the metal jet. The insertion of material, however, greatly increases the total amount of material required for the safe packaging of munitions. It becomes important, therefore, to develop a model of the shield interaction with such shell casing jets to facilitate the development of optimum packaging designs capable of inhibiting influence initiation of shells in this severe environment.

The design of an optimum packaging involves variation of numerous parameters such as number, thickness, composition, and placement of the shield materials. Extensive experimental work has been carried out to determine good potential designs[1-4]. Still, determination of an optimum design requires the development of a mathematical model to minimize the total number of experimental tests necessary for the development of the influence suppression configuration. The purpose of the present report is to provide a model of the antifratricide shield panels subjected to the most severe environment, jets produced by simultaneously detonating neighboring rounds. A subsequent report will deal with the problem of shock attenuation by panels separating neighboring rounds.

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[1] *Howe, P.M., "The Phenomenology of Interround Communication and Techniques For Prevention," ARBRL-TR-02048 (1978) (AD#A054373).*

[2] *Howe, P.M., Collis, D., "Effectiveness of Plastic Shields in Prevention of Propagation of Reaction Between Compartmentalized Warheads," ARBRL-MR-02827 (1978) (AD#B027466L).*

[3] *Howe, P.M., "The Response of Munitions to Impact," ARBRL-TR-02169 (1979) (AD#B040230).*

[4] *Gibbons, Jr., Gould, "Multiple Round Fragmentation Hazards and Shielding," ARBRL-TR-02329 (1981). (AD #B058793L)*

II. DESCRIPTION OF THE ARTILLERY SHELL METAL JET

The mechanism causing influence initiation of concern in the present report is the jetting of metal due to the impact of shell casing material from two neighboring shells initiated at approximately the same time. An example of the formation of a jet resulting from the simultaneous detonation of two Comp B filled steel pipe bombs (15.2 cm long, 4.83 cm diameter, 3.2 mm thick wall) is seen in the end-on flash X-ray photograph, Fig. 1. The details of the jets formed by this mechanism vary considerably from shot to shot (largely because the pipe bombs are not precision items). Typically, the jets travel at about 2 km/s with the lowest velocity material effective in penetrating metal plates traveling at about 0.5 km/s. Material in the jet is confined to a fan of material about 0.1 radian in angular width.

The design of an optimum suppressive structure requires that this type of jet be either interrupted, dissipated or inhibited. We describe below the model used to calculate the effect of jet collision with elements of the suppressive structure.

III. ARTILLERY SHELL INFLUENCE INITIATION EFFECTS

Impact of explosively accelerated metal on artillery shells can produce influence initiation by any of the following mechanisms:

(1) Shock loading of the explosive arising from metal on metal impact leading to the incidence of a strong shock propagating into the explosive.

(2) Adiabatic compression or plastic flow heating of the explosive (or entrapped gas) due to compressive deformation of the impacted shell or to fragment penetration.

(3) Plastic flow heating of explosive injected into shell fissures formed by metal on metal impact.

(4) Direct exposure of the explosive fill to hot fragments in the explosive environment due to shell wall failure or penetration.

These mechanisms entail different quantitative criteria to determine if initiation will be produced in a given test situation. These include:

(1) The time integral of the shock pressure p squared, $\int p^2 dt$. This quantity can be compared with critical values for different explosives.

(2) The maximum pressure to which the explosive is subjected during shock loading, p_{max}, and the rate of loading dp/dt of the explosive or entrapped gas.

(3) A shell deformation characteristic measure Δ,

$$\Delta = \iint \frac{p-\sigma}{\rho} \, dt \, dt$$

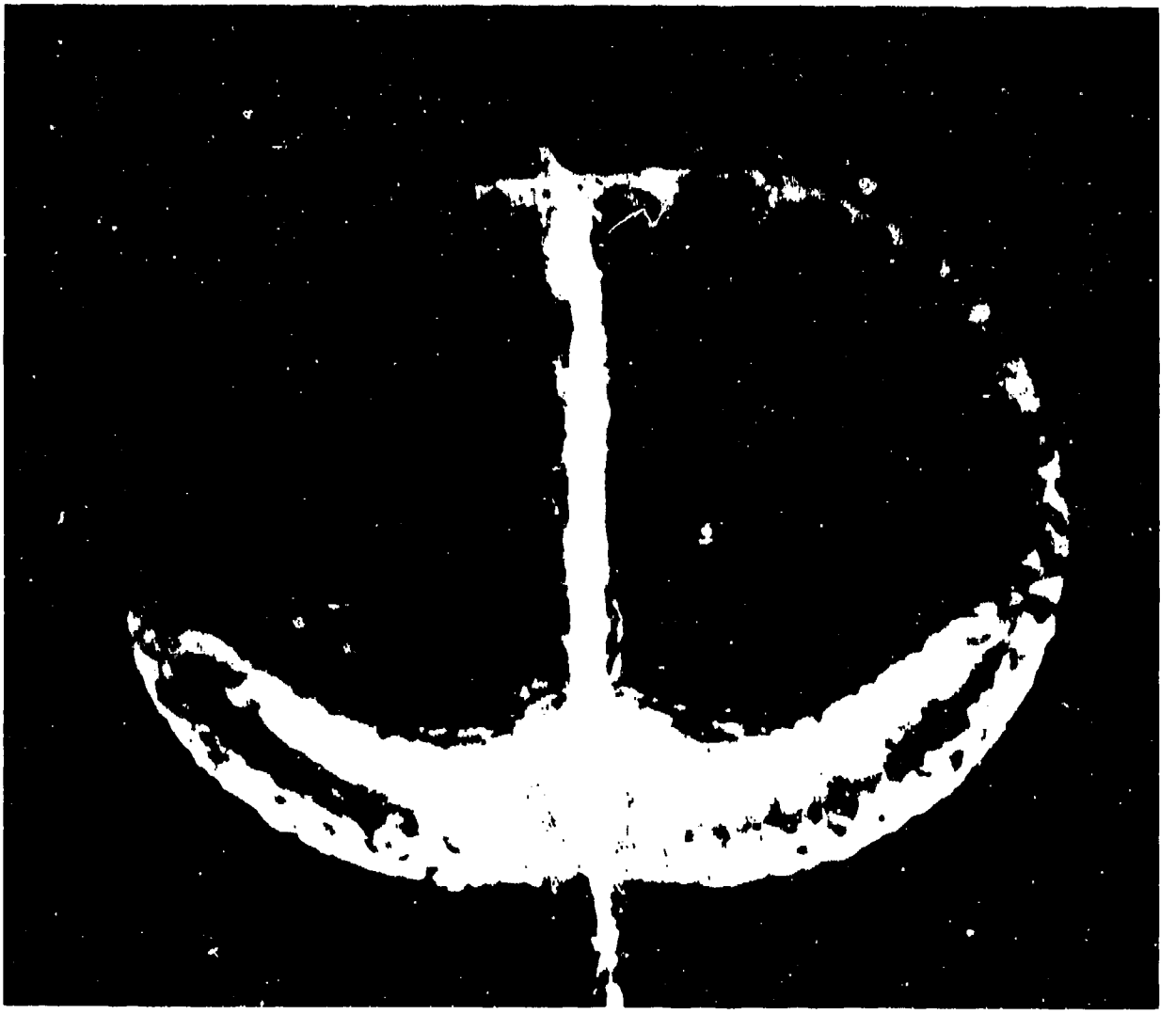

Figure 1. Flash X-ray photograph of two Comp B filled steel pipe bombs from end-on view. The pipe bombs are 15.2 cm long, 4.83 cm in diameter with 3.2 mm thick walls and separated by a distance of 6.35 mm. The flash X-ray was taken 50.1 μs after detonation of the rounds. The vertical stripe in the X-ray photograph is caused by the metal jet, which of course, is traveling with a velocity gradient.

where σ is the effective strength of the shell wall material (taking account of moment arm effects in the loading), and ρ is the density of the material.

(4) Depth of penetration of impacting fragments or jets into the casing of the artillery shell.

In the present report we will only be concerned with the last of these, the penetration depth into the wall, as from the experimental data it appears that this is the most critical measure in determining whether or not metal jetting will lead to HE initiation.

IV. DESCRIPTION OF THE INFLUENCE SUPPRESSIVE STRUCTURE PARAMETERS FOR THE ARTILLERY SHELL PACKAGING AND STORAGE SHIELDS

Experimental tests[3,4] have demonstrated that the use of multiple sheets of material (perpendicular to the line joining the center of the detonated or donor shell and the protected or acceptor shell) proves to be effective in suppressing influence initiation. Plaster, containing water of hydration, has appeared to be a particularly good material for use in these experiments.[4] In addition the use of explosive material sandwiched between layers of inert material may prove to be a good material to shield artillery shells from metal jets. As such, a typical shield design may have as many as six layers, each of which must be designed to be of optimum thickness and placement. Figure 2 shows the general configuration to be treated in the present paper. Since plaster contains water of hydration, there is the possibility for it to behave as an active material in these structures. The high velocity impact of metal from an exploding shell gives rise to shocks in the plaster, producing shock heating of the material. This heating can liberate water from the gypsum in the form of steam, driving the material as though it had exploded.

In the following treatment of the suppressive structure, Fig. 2 will be used as the basis for the physical configuration to be treated by the model. For the most part, materials, dimensions, etc. will be represented parametrically. Subsequently the model will be exercised to determine those characteristics yielding the best results under various constraints (such as total weight or volume).

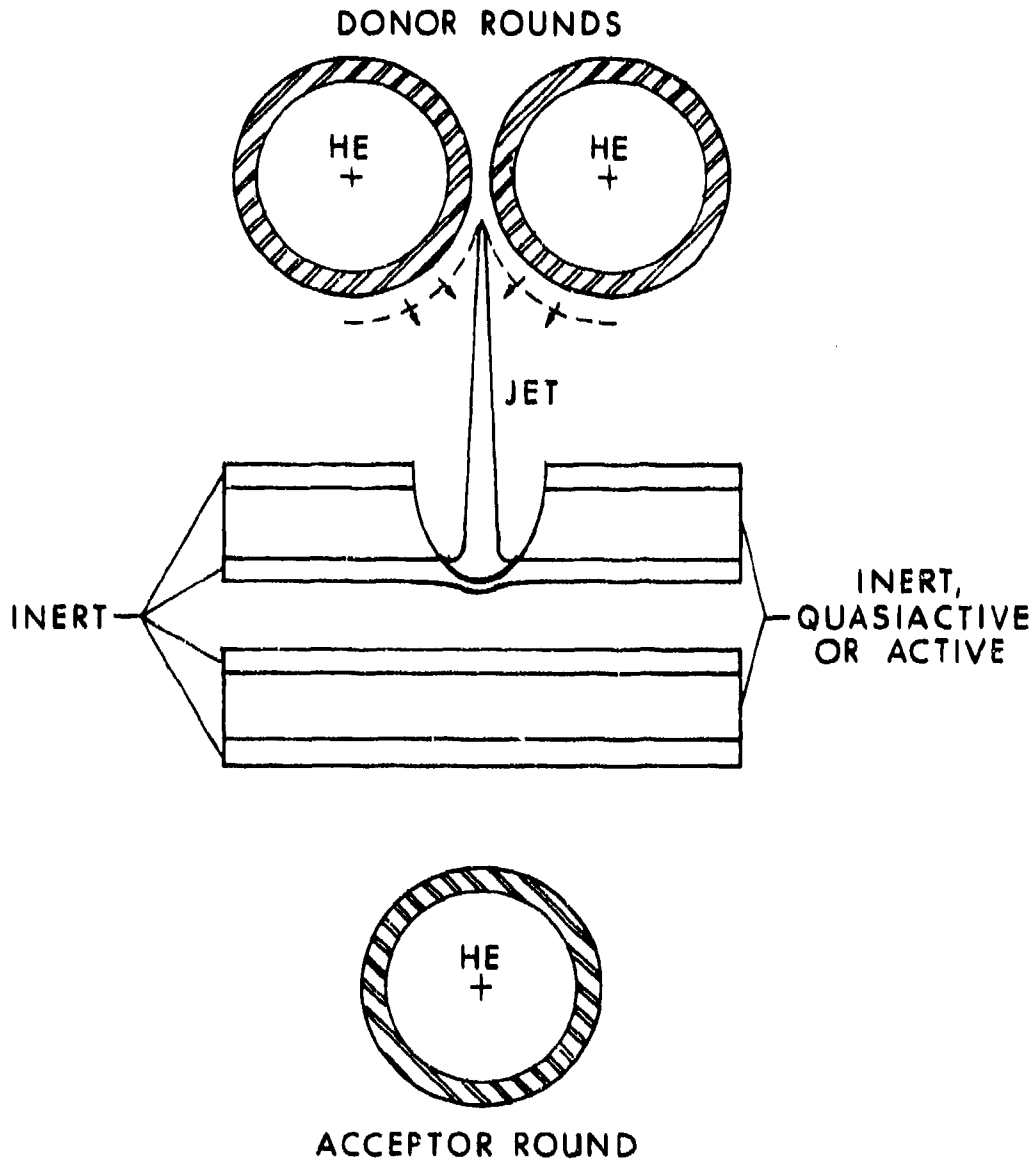

Figure 2. General configuration of shields treated in the present paper. The donor shells are assumed placed in the worst case position relative to the acceptor shell. Two shields each of up to three layers of any thickness are assumed placed at any position between the donor and acceptor shells. The middle layer of each shield is assumed to consist of an inert material, a semiactive material such as plaster with water of hydration, or an explosive material.

V. SHOCK ACTIVATION AND JET PENETRATION OF HYDRATED OR EXPLOSIVE SOLIDS

Use of gypsum in the form of plaster panels has yielded some experimental data[4], suggesting that under shock loading the material responds in an explosive manner. Sufficiently strong shock can give rise to the heating of the granular solid material comprising these panels. The heat acts to calcine the plaster giving rise to a high temperature steam under elevated pressures. As a result some of the original shock energy can be dissipated in the plaster. The subsequent explosive expansion of the plaster, however, may give rise to shocks in neighboring materials. Shocks propagating through water, however, have not exhibited any increased ability to attenuate shocks from donor rounds. Thus, there may exist an effect due to shock induced calcination that involves the "solid residuum" serving as the source of the heat available for the generation of the steam.

Let us assume that we have a completely inelastic collision between a plate of areal density σ_1 (volumetric density ρ_1) traveling at an initial velocity v_1 and a stationary plaster plate of areal density σ_2 (volumetric density ρ_2) containing a fraction g of moisture as shown in Fig. 3. After the collision the velocity (of the center of mass) is v_2. The energy absorbed per unit area E is given by

$$E = \tfrac{1}{2}\left[P_1^2/\sigma_1 - P_2^2/(\sigma_1 - \sigma_2)\right] \tag{1}$$

where

$$P_1 = \sigma_1 v_1 \tag{2}$$

and

$$P_2 = (\sigma_1 + \sigma_2)v_2 \tag{3}$$

The specific energy ϵ_2, per unit mass in the second (plaster) plate before expansion is

$$\epsilon_2 = E/\sigma_2 \tag{4}$$

This energy gives rise to the heating of the "solid residuum" of specific heat C_{v_s} (which for plaster has a value of 0.210 cal/g°C), and the water of specific heat $C_{v_{H_2O}}$ (=0.48 cal/g°K) that is liberated as the gypsum is heated. The heat of liberation is represented by h_f. For gypsum, h_f is 58.1 cal/g; for water, 79.7 cal/g. We obtain

$$\epsilon_2 = (1 - g)C_{v_s}\Delta T + C_{v_{H_2O}}\Delta T + gh_f \tag{5}$$

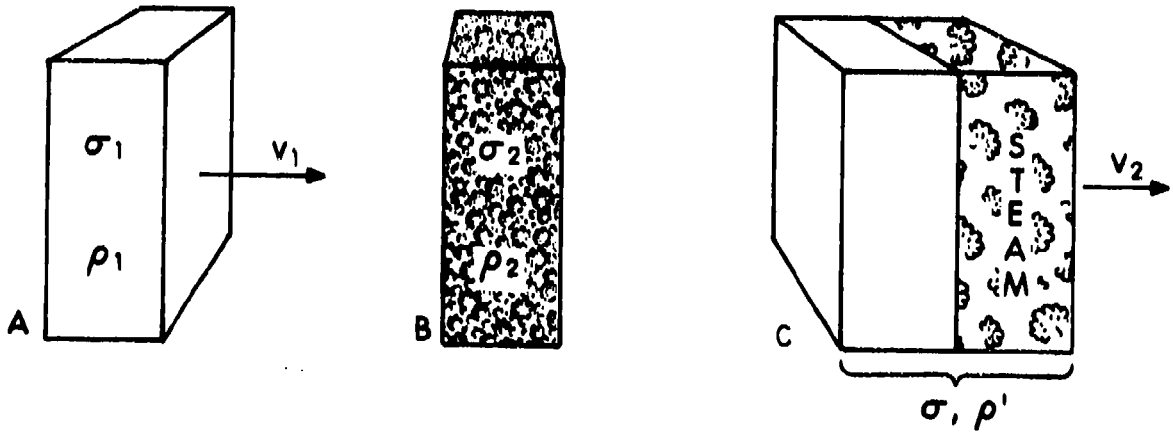

Figure 3. Schematic of an inelastic collision between an inert plate, A, traveling with velocity v_1 impacting on a plate containing water (for example, a plaster panel containing water of hydration) content, B. The resultant combination of plates, C, travels away with a velocity v_2, the kinetic energy absorbed by the inelastic collision being converted to heat with the evolution of steam.

(This expression represents the unexpanded condition of the heated plaster so that the heat of vaporization does not occur here.) where $\Delta T = T - T_i$, T_i being the initial temperature of the plaster and T the temperature to which an amount ε_2 of energy heats the plaster. Of this, an energy (specific) ε_{H_2O} will be available as the explosively released energy of the steam. Where $gC_{v_{H_2O}} \Delta T$ is the energy that goes into heating the liberated water, the available energy is

$$\varepsilon_{H_2O} = gC_{v_{H_2O}} \Delta T n \tag{6}$$

where n is the work efficiency. We will use for n the ideal thermodynamic efficiency (for a Carnot cycle) although the actual efficiency is lower. The ideal efficiency is

$$n = \frac{T - T_i}{T} \tag{7}$$

Where T is high, Eq. (8) serves as a good approximation. Thus, we can write

$$2\varepsilon_{H_2O}/n = [\sigma_1 v_1^2 - (\sigma_1 + \sigma_2)v_2^2]/\sigma_2 - 2[(1 - g)C_{v_s} \Delta T + gh_f] \tag{8}$$

or substituting for ΔT from Eq. (8) and solving for ε_{H_2O} we have

$$2\varepsilon_{H_2O} = n\left\{\sigma_2[\sigma_1 v_1^2 - (\sigma_1 + \sigma_2)v_2^2] - 2gh_f\right\} / [1 + (\frac{1 - g}{g})\frac{C_{v_s}}{C_{v_{H_2O}}}] \tag{9}$$

The quantity $2\varepsilon_{H_2O}$ can be used as the energy constant in the Gurney equation in order to calculate the subsequent expansion of the plaster plate as it drives adjoining plates. It should be noted that the assumption of complete inelastic collision leads to Eq. (5) giving the energy available for calcination of the gypsum. In the case where a given shock propagates into a panel, it is necessary to determine the rate at which shock energy is converted to heat which will be a function of (1 - g). The value for dry gypsum (water of hydration) is 0.209. Measurements by Gould Gibbons, Jr. (TBD - EEB) yielded a value of 0.290 for wet plaster as tested.

Let us now consider what occurs when a high velocity jet of material impacts a material such as plaster which explosively releases energy. Figure 4 shows the flow of jet material and target material in the coordinate system moving with the stagnation point in a target under steady state flow conditions. Letting v_j be the velocity of the jet and V_s the velocity of the stagnation point, in the frame of reference moving with the stagnation point, the jet approaches the stagnation point S with a velocity $v_j - V_s$ while the target material approaches with a velocity V_s. To maintain steady state

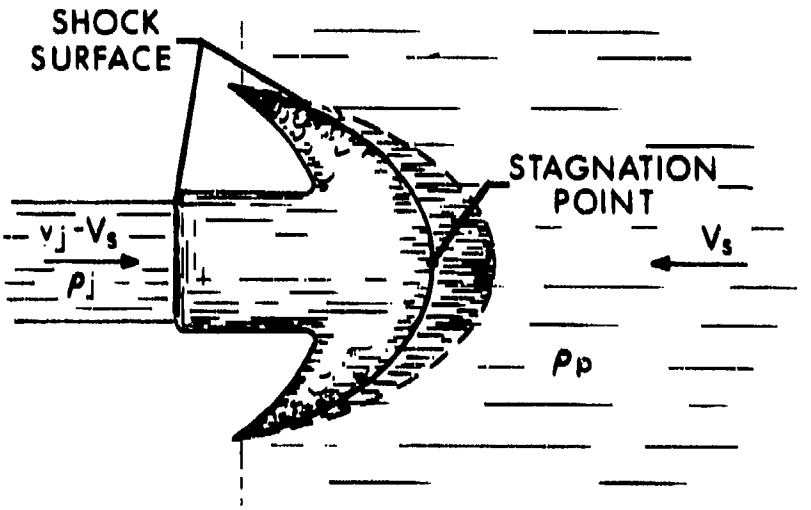

Figure 4. Schematic of a jet interaction with a target material under conditions of hypervelocity flow. Velocity vectors give velocities with respect to a coordinate system moving to the right with the stagnation velocity V_s.

flow, the forces acting on the stagnation point must be balanced. Therefore, we can write, noting that the shocked plaster gives rise to a pressure p_{H_2O},

$$\tfrac{1}{2}\rho_j(v_j - V_s)^2 = \tfrac{1}{2}\rho_i V_s^2 + p_{H_2O} \tag{10}$$

We note that p_{H_2O} is simply equal to the energy density of the steam, ε_{H_2O}, as given by Eq. (9). By reference to Fig. 3 and recognizing that in jet penetration to an incremental depth dP an incremental length of penetrator dL impacts with the target and is consumed, we see that the quantities σ_1 and σ_2 of Eq. (9) take the values

$$\sigma_1 \rightarrow dL\rho_j \tag{11}$$

and

$$\sigma_2 \rightarrow dP\rho_p \tag{12}$$

Where

$$v_1 = v_j \tag{13}$$

we have

$$\sigma_1 v_1 = (\sigma_1 + \sigma_2)v_2 \tag{14}$$

or

$$v_2 = v_j/(1 + \frac{\sigma_2}{\sigma_1}) = v_j(1 + \frac{dP\rho_t}{dL\rho_j}) \tag{15}$$

Therefore, we have the integral expression for P

$$P = \int_0^L dL\sqrt{\rho/(1 + \alpha)} \tag{16}$$

where

$$\rho = \rho_j/\rho_p \tag{17}$$

$$\alpha = 2p_{H_2O}/\rho_p V_s^2 \tag{18}$$

and

$$p_{H_2O} = \rho_p \varepsilon_{H_2O} \tag{19}$$

Where ρ and α are constant, we can write (16) as

$$P = L\sqrt{\rho/(1 + \alpha)}. \tag{20}$$

Substituting from (13) and (14) into (9) gives

$$\epsilon_{H_2O} = \tfrac{1}{2}\eta k\left[v_j^2\left(\frac{\sigma_1}{\sigma_2} - \frac{\sigma_2}{\sigma_1 + \sigma_2}\right) - 2gh_f\right] \tag{21}$$

where

$$k = \left[1 + \frac{(1 - g)C_{V_s}}{gC_{V_{H_2O}}}\right]^{-1}. \tag{22}$$

Defining

$$f = \sigma_1/\sigma_2 = \rho\frac{dL}{dP}, \tag{23}$$

we can write (21) as

$$\epsilon_{H_2O} = \tfrac{1}{2}\eta k\left[v_j^2\left(\frac{f^2 + f - 1}{1 + f}\right) - 2gh_f\right]. \tag{24}$$

Substituting (24) into (19) and then into (18) gives

$$\alpha = \begin{cases} \eta k\left[v^2\left(\dfrac{f^2 + f - 1}{f + 1}\right) - \delta\right] \\ 0 \qquad \text{if } \eta k\left[v^2\left(\dfrac{f^2 + f - 1}{f + 1}\right) - \delta\right] < 0 \end{cases} \tag{25}$$

where $v = v_j/V_s$ and

$$\delta = 2gh_f/V_s^2. \tag{26}$$

If we take the effects of the steam evolution to be small then

$$f = \frac{\rho}{dP/dL} \quad \frac{\rho}{\sqrt{\rho}} = \sqrt{\rho}\ . \tag{27}$$

With this value as an approximation, Eq. (25) can be solved iteratively allowing the integration of Eq. (16). It may be seen that Eqs. (20) and (28) abridge the usual penetration density law for hypervelocity target penetration, giving rise to a term that increases the effecti.e density of the target material. Thus, in the case of impact activated materials the usual hypervelocity penetration density law differs from that appropriate for inert materials.

VI. DESIGN OPTIMIZATION FORMULATION FOR INFLUENCE ATTENUATION PANELS TO SUPPRESS SHELL - SHELL IMPACT JET INDUCED INITIATION

Assume a jet formed by the impact of two simultaneously initiated shells, as shown in Fig. 1, attacks an influence suppression structure of the kind shown in Fig. 2. Figure 5 illustrates the specific jet and suppressive structure concerned together with parameters representing the important dimensions and quantities. Assume the jet formed by the impact of the shells has an initial length ℓ of density ρ_o, the density of the shell walls, and that subsequently the jet increases in length linearly with the difference between the jet tip velocity v_t and jet back velocity v_b. We assume also that the jet width increases from an initial value e with a velocity $\alpha v(x)$ where α is a constant equal to the angle of spread in jet material measured in radians and $v(x)$ is the forward velocity of the jet at any distance x along the initial jet length. The density of the jet is assumed to decrease inversely with the product of the fractional increase in width and local stretching in length.

We assume a linear velocity gradient given at any point x by

$$v = v_b + (v_t - v_b)x/\ell \tag{28}$$

where ℓ is the length of the jet at which the density is that of the steel. The time for material to reach any distance L will be referred to the time of initial jetting (virtual origin of the jet at x=0). Thus,

$$t(x) = L/v(x). \tag{29}$$

The jet element of length dx at x increases in length to dx' as of its arrival at L as given by

$$dx' = dx + tdv \tag{30}$$

Differentiating Eq. (28) to substitute for dv and using (29) to substitute for t in (30) gives on integrating

$$x' = [1 + C_1 L/(1 + C_1 x)]dx \tag{31}$$

$$= \ell + L \ln(1 + C_1 \ell)$$

where

$$C_1 = (v_t - v_b)/\ell v_b. \tag{32}$$

This gives the length of the jet at any distance L from its origin.

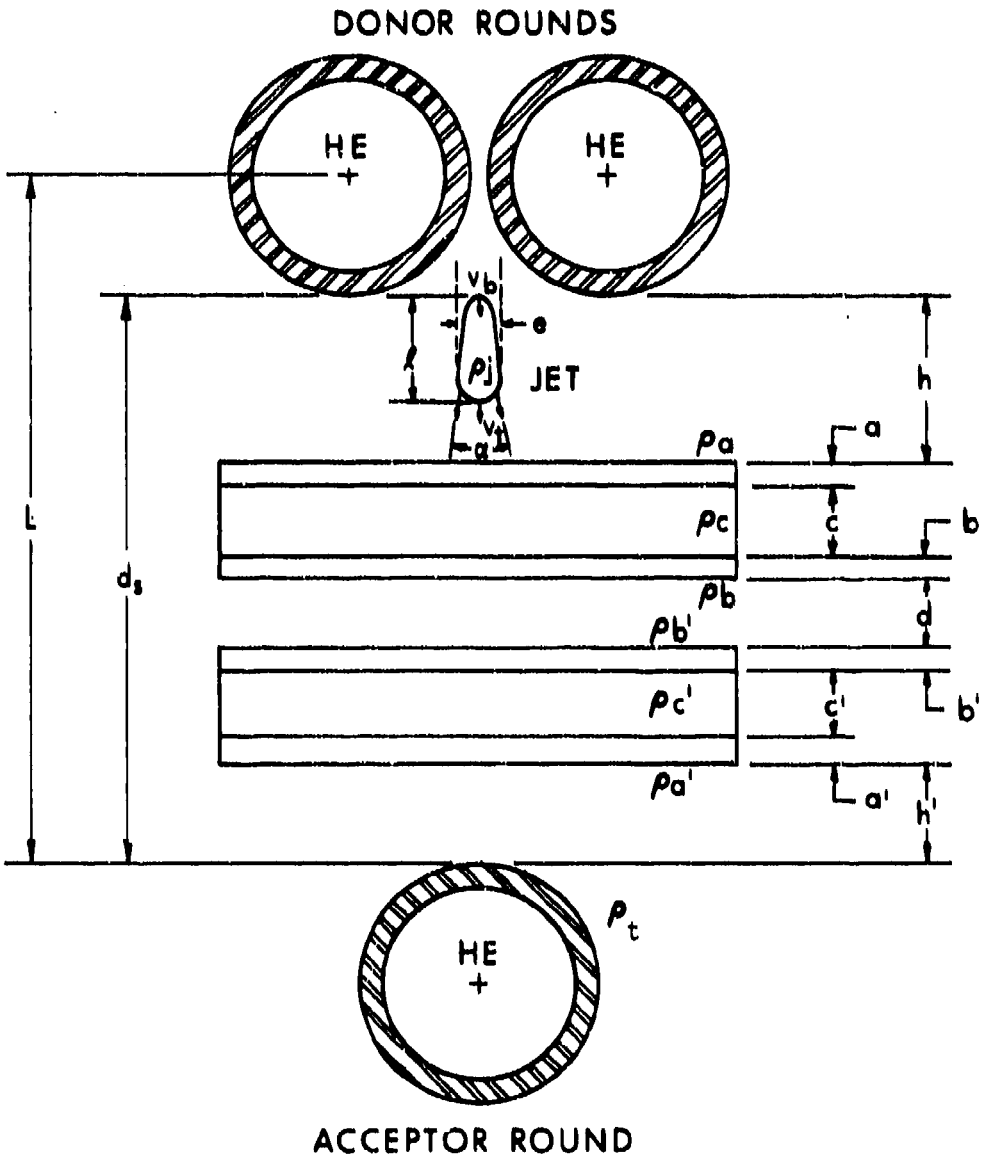

Figure 5. Schematic of the jet formed by simultaneously initiated artillery shells and antifratricide panels of the type shown in Fig. 2 defining the important parameters governing the interaction. Jet tip and base velocities v_t, v_b, width e, angular spread α, initial length ℓ and jet density ρ_j, panel densities ρ_a, ρ_b, ρ_c, $\rho_{a'}$, $\rho_{b'}$, and $\rho_{c'}$, as well as the spacial configurational parameters, c', h, d, d_s and L are shown. Density of the target is ρ_t.

The penetration of the unimpeded jet at L in a target (such as steel) of density ρ_t must be calculated in terms of the density of the jet as it arrives at the target. Since the jet initially forms a sheet of metal, its density drops as it expands laterally, i.e., normally to the surface of that sheet, and as it lengthens. Thus, we have for the density:

$$\rho_j(x,t) = \rho_o \frac{e}{e + \alpha v(x) t(x)} \left(\frac{dx'}{dx}\right)^{-1} \tag{33}$$

$$= \rho_o \left(1 + \frac{C_1 L}{1 + C_1 x}\right)^{-1} \frac{e}{e + \alpha v t} .$$

The penetration factor is $\sqrt{\rho_j/\rho_t}$. Thus, without influence suppression panels, the penetration P in the target at L will be

$$P = \int_0^{\ell} dx \sqrt{\rho_j/\rho_t} \left[1 + \frac{C_1(L + P(x))}{1 + C_1 x}\right] \tag{34}$$

where we have included the penetration into the target L + P(x) as a correction to more accurately give the distance to the target. This correction is to be included in the expression for ρ_j as well, but only for the longitudinal extension of the jet:

$$\rho_j(x,t) = \rho_o \left(1 + \frac{C_1(L + P(x))}{1 + C_1 x}\right)^{-1} \frac{e}{e + \alpha L} . \tag{35}$$

This gives for the penetration into the target in the absence of suppressive layers:

$$P \sqrt{\rho_o/\rho_t} \int_0^{\ell} dx \left(1 + \frac{C_1(L + P_x)}{1 + C_1 x}\right)^{1/2} \Bigg/ \left(1 + \frac{\alpha}{e} L\right)^{1/2} \tag{36}$$

where the notation P_x means

$$P_x \equiv P(x) = \sqrt{\rho_o/\rho_t} \int_0^{x} dx \left(1 + \frac{C_1(L + P_x)}{1 + C_1 x}\right)^{1/2} \Bigg/ \left(1 + \frac{\alpha}{e} L\right)^{1/2} \tag{37}$$

We now calculate the effects due to the presence of two suppressive structure panels through which the jet must pass before encountering the target plate. Assume panel 1 consists of the three layers of thickness a, c, and b as shown in Fig. 6. We have for the losses of jet length $\Delta\ell_a$,

$\Delta\ell_c$, $\Delta\ell_b$

$$a = \sqrt{\rho_o/\rho_a}\int_{\ell-\Delta\ell_a}^{\ell} dx\left[1 + \frac{C_1(h + P_a)}{1 + C_1 x}\right]^{1/2} \Bigg/ \left(1 + \frac{\alpha}{e}\, h\right)^{1/2} \qquad (38)$$

$$c = \sqrt{\rho_o/\rho_1}\int_{\ell-\Delta\ell_a-\Delta\ell_c}^{\ell-\Delta\ell_a} dx\left[1 + \frac{C_1(h+a+P_c)}{1 + C_1 x}\right]^{1/2} \Bigg/ \left[1 + \frac{\alpha}{e}\,(h + a)\right]^{1/2} \qquad (39)$$

and

$$b = \sqrt{\rho_o/\rho_b}\int_{\ell-\Delta\ell_a-\Delta\ell_c-\Delta\ell_b}^{\ell-\Delta\ell_a-\Delta\ell_c} dx\left[1 + \frac{C_1(h+a+c+P_b)}{1 + C_1 x}\right]^{1/2} \Bigg/ \left[1 + \frac{\alpha}{e}\,(h+a+c)\right]^{1/2} \qquad (40)$$

where P_a, P_c, and P_b are defined as the instantaneous penetration as in Eq. (37). The density ρ_1 is from (20), the "effective" value

$$\rho_1 = \rho_c(1 + \alpha) \qquad (41)$$

For high velocity jet penetration, stagnation point temperatures are high, so that the efficiency η can be nearly unity. In this case (41) becomes

$$\rho_1 = \rho_c\left\{1 + k\left[v^2\left(\frac{f^2+f-1}{f+1}\right) - \delta\right]\right\} \qquad (41a)$$

which is to be solved recursively. The total loss in length passing through panel 1 is therefore $\Delta\ell_1$ where

$$\Delta\ell_1 = \Delta\ell_a + \Delta\ell_c + \Delta\ell_b \qquad (42)$$

During the jet's penetration of panel 1, a shock builds up in the jet as shown in Fig. 4. When the jet exits panel 1, the rarefaction wave from the newly formed free surface of the jet propagates into this region of high pressure, disrupting the jet material. Let us obtain an approximate expression for the loss of jet material due to this effect. There are two cases to be considered. First, if the penetration is supersonic an amount proportional (and approximately equal) to the jet thickness is lost, i.e., and amount ke_1, where k is a proportionality constant approximately equal to unity. Since this should be expressed so that a zero thickness panel removes no jet material we will write for the loss length

$$y_1 = ke_1/\ [1 + e_1\rho_{j_1}/(a\rho_a + b\rho_b + c\rho_1)] \tag{43}$$

where e_1 is the jet width given in terms of the initial width by

$$e_1 = e/[1 + \frac{\alpha}{e}\ (h + a + b + c)] \tag{44}$$

and ρ_{j_1} is the density of the jet on exit from the first panel. In this length y_1, shocks of pressure p_1 given by

$$p_1 = \frac{\rho_1\rho_{j_1}}{2(\sqrt{\rho_1} + \sqrt{\rho_{j_1}})^2}\ v_1^2 \tag{45}$$

where ρ_1 should be taken to be the average density within a mass column equal to e_1y_1, act on the mass column. In essence this means $\rho_1 = \rho_b$ unless $b \ll e$ or $\rho_b \ll \rho_j$. Also, ρ_{j_1} should be taken to be the jet density at exit from panel 1:

$$\rho_{j_1} = \rho_o \left(1 + \frac{C_1(h+a+b+c)}{1+C_1(\ell-\Delta\ell_1)}\right)^{-1} \frac{e}{e+\alpha(\ell-\Delta\ell_1)} \tag{46}$$

Here v_1 is the corresponding velocity at $x = \ell - \Delta\ell_1$ as given by Eq. (38). Now the pressure p_1 causes the jet to spread laterally and thus drop in effectiveness against the next plate. This loss in effective length Δy_1 is calculated from density considerations to be

$$\Delta y_1 = -y_1\ [1 - \sqrt{(1 + \alpha d/e)/\ (1 + \alpha f_1 d/e)}\ ] \tag{47}$$

where

$$f_1 = \frac{\alpha v_1}{\alpha v_1 + (p_1/\rho_{j_1})^{1/2}} \tag{48}$$

In the case of subsonic penetration of the panel, the shock zone in the jet will increase with penetration distance. However, the strength of the shock will decrease. Thus, Eq. (47) will serve as an approximation of the jet length loss in that case as well. This length loss is equivalent to an initial length decrement $\Delta\ell_1'$ given by

$$\Delta y_1 = \int_{\ell-(\Delta\ell+\Delta\ell_1')}^{\ell-\Delta\ell_1} dx \left[1+ \frac{C_1(h + a + b + c + d)}{1 + C_1 x}\right] . \qquad (49)$$

At panel 2 the length loss is to be computed in the same fashion as for the first panel. We have in the appropriate order:

$$b' = \sqrt{\rho_o/\rho_{b'}} \int_{\ell-(\Delta\ell_1+\Delta\ell_1')-\Delta\ell_{b'}}^{\ell-(\Delta\ell_1+\Delta\ell_1')} dx \left[1 + \frac{C_1(L_2 + P_{b'})}{1 + C_1 x}\right]^{1/2} \Bigg/ \left[1 + \frac{\alpha}{e} L_2\right]^{1/2} \qquad (50)$$

where

$$L_2 = h + a + b + c + d \qquad (51)$$

$$c' = \sqrt{\rho_o/\rho_2} \int_{\ell-(\Delta\ell_1+\Delta\ell_1')-\Delta\ell_{b'}-\Delta\ell_{c'}}^{\ell-(\Delta\ell_1+\Delta\ell_1')-\Delta\ell_{b'}} dx \left[1 + \frac{C_1(L_2+b'+P_{c'})}{1 + C_1 x}\right]^{1/2} \Bigg/ \left[1 + \frac{\alpha}{e} (L_2+b')\right]^{1/2} \qquad (52)$$

and

$$a' = \sqrt{\rho_o/\rho_{a'}} \int_{\ell-(\Delta\ell_1+\Delta\ell_1')-\Delta\ell_2}^{\ell-(\Delta\ell_1+\Delta\ell_1')-\Delta\ell_{b'}-\Delta\ell_{c'}} dx \left[1+ \frac{C_1(L_2+b'+c'+P_{a'})}{1 + C_1 x}\right]^{1/2} \Bigg/ \left[1 + \frac{\alpha}{e} (L_2+b'+c')\right]^{1/2} \qquad (53)$$

where

$$\Delta\ell_2 = \Delta\ell_{a'} + \Delta\ell_{b'} + \Delta\ell_{c'} . \qquad (54)$$

As in the case for Eq. (41), we write for ρ_2

$$\rho_2 = \rho_{c'} (1 + \alpha') = \rho_{c'} \left\{ 1 +k \left[v^2 \frac{f^2 + f - 1}{f + 1} - \delta \right]\right\} . \qquad (55)$$

Again we calculate the effective loss in jet length due to shocks in the jet on exit from the second panel. Corresponding to Eq. (43) to (49) we have

$$y_2 = ke_2/[1 + e_2\rho_{j_2}/(a'\rho_{a'} + b'\rho_{b'} + c'\rho_2)] \qquad (56)$$

with

$$e_2 = e/[1 + \frac{\alpha}{e}(L_2 + a' + b' + c')]. \tag{57}$$

The shock pressure p_2 is

$$p_2 = \frac{\rho_2 \rho_{j_2}}{2(\sqrt{\rho_2} + \sqrt{\rho_{j_2}})^2} v_2^2 \tag{58}$$

where

$$\rho_{j_2} = \rho_o \left(1 + \frac{C_1(L_2+a'+b'+c')}{1+C_1(\ell-\Delta\ell_1-\Delta\ell_1'-\Delta\ell_2)}\right)^{-1} \frac{e}{e+\alpha(\ell-\Delta\ell_1-\Delta\ell_1'-\Delta\ell_2)} \tag{59}$$

and v_2 is the velocity at $x = \ell-\Delta\ell_1-\Delta\ell_1'-\Delta\ell_2$ as given by Eq. (38). The spread in the jet produces the effective loss

$$\Delta y_2 = -y_2[1 - \sqrt{(1 + \alpha h'/e)/(1 + \alpha f' h'/e)}\ ] \tag{60}$$

where

$$f' = \frac{\alpha v_2}{\alpha v_2 + (p_2/\rho_{j_2})^{1/2}} \tag{61}$$

Therefore, $\Delta\ell_2'$, the effective loss in initial rod length due to the gap h' is

$$\Delta y_2 = \int_{\ell-(\Delta\ell_1+\Delta\ell_1')-\Delta\ell_2+\Delta\ell_2'}^{\ell-(\Delta\ell_1+\Delta\ell_1')-\Delta\ell_2} dx \left[1 + \frac{C_1(L_2+a'+b'+c'+h')}{1 + C_1 x}\right] \tag{62}$$

Finally, the remaining rod material penetrates into the target a distance

$$p' = \sqrt{\frac{\rho_o}{\rho_t}} \int_0^{\ell-(\Delta\ell_1+\Delta\ell_1')-(\Delta\ell_2+\Delta\ell_2')} dx \left[1 + \frac{C_1(L+P'x)}{1 + C_1 x}\right]^{1/2} \Bigg/ \left(1 + \frac{\alpha}{e} L\right)^{1/2} \tag{63}$$

VII. COMPUTATIONS

A computer code designated "Main" to compute P' has been developed and is given in Appendix A. This code has been used to compute shield effectiveness curves. The effectiveness of a single homogeneous panel to suppress jet induced influence is shown in Figs. 6-9. The nondimensional penetration (in units of donor round radius) P' as a function of the nondimensional panel thickness (also in units of donor round radius) is plotted for the case of separation distance d_s equal to 1.0 R (Fig. 6), 2.0 R (Fig. 7), 3.0 R (Fig. 8), and 4.0 R (Fig. 9). The shield panel is taken to be equidistant between the donor and acceptor rounds. Panel density ρ_c is taken as a parameter for Figs. 6-9. Values of specific parameters have been taken to provide an optimum fit to experimental data obtained from pipe bomb tests as discussed below.[4] X-rays made during these pipe bomb tests were employed to obtain the jet characteristic parameters' values. Specific values used are:

Jet Characteristics: $\rho_o = 8.0$ g/cm^3

$\ell = 0.2$

$e = 0.4$

$\alpha = 0.1$

$v_t = 2.0$ km/s

$v_b = 0.5$ km/s

Target: $\rho_t = 8.0$ g/cm^3

Other: $k = 2.0$

$v_s = 3.0$ km/s

$g = 0.0$ and 0.209

The results obtained for the two values of g were nearly the same. The values of jet characteristic parameters are dependent on the donor rounds used. For rounds that do not scale to the approximate values of the pipe bombs used in Ref. 4, scaling test should be made before the results of Figs. 6-9 are used for applications. The curves offer no surprises, but simply show that increased thickness and increased density both decrease monotonically the penetration in an acceptor round. The curves can be used to obtain the requirements to just stop a jet from penetrating into the acceptor.

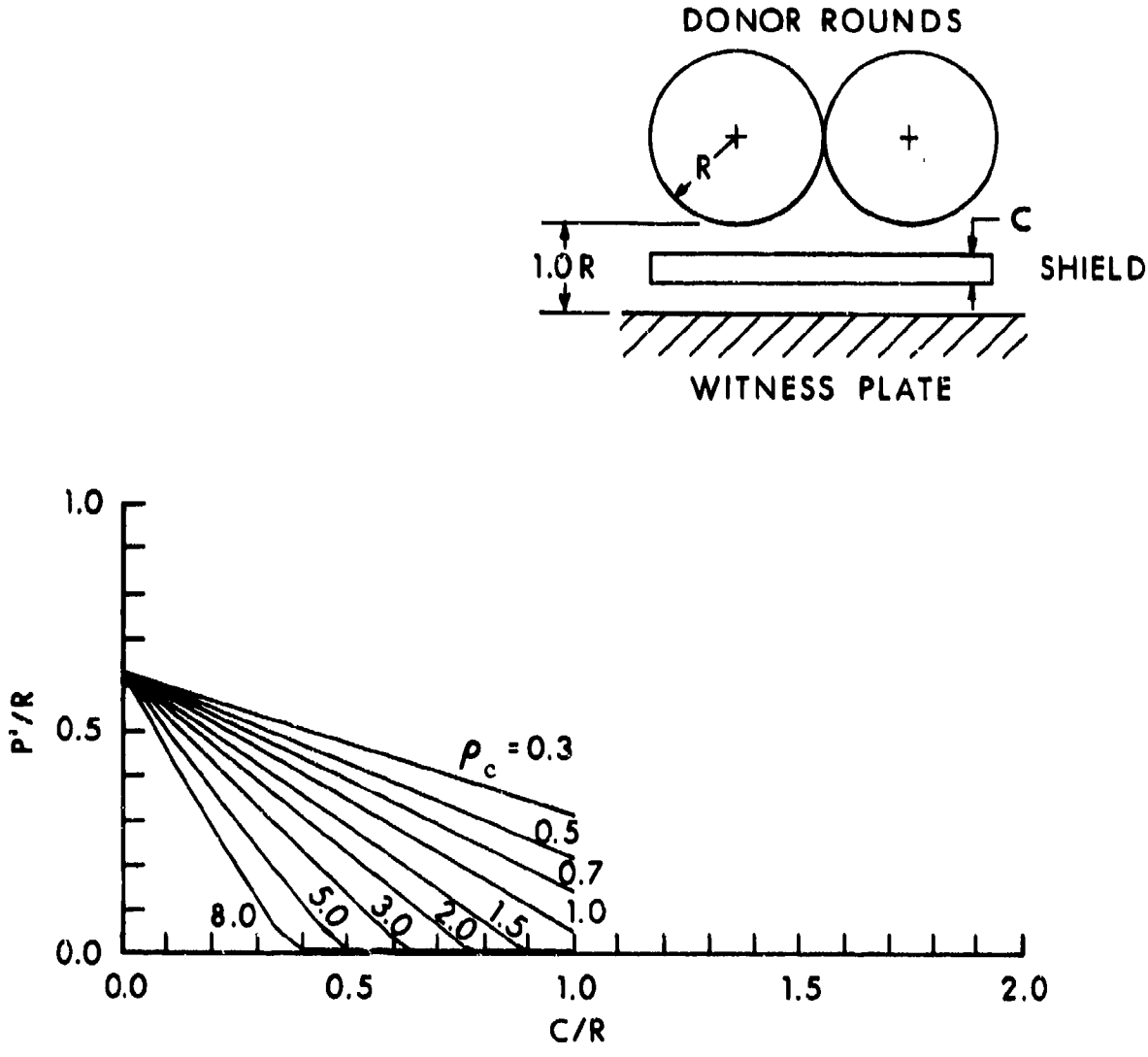

Figure 6. Nondimensional penetration P'/R versus nondimensional shield thickness C/R, where shield is placed at midpoint between donor and acceptor rounds (or witness plate, as shown in inset) separated by 1.0 R. Shield density ρ_c is parameter for the family of curves.

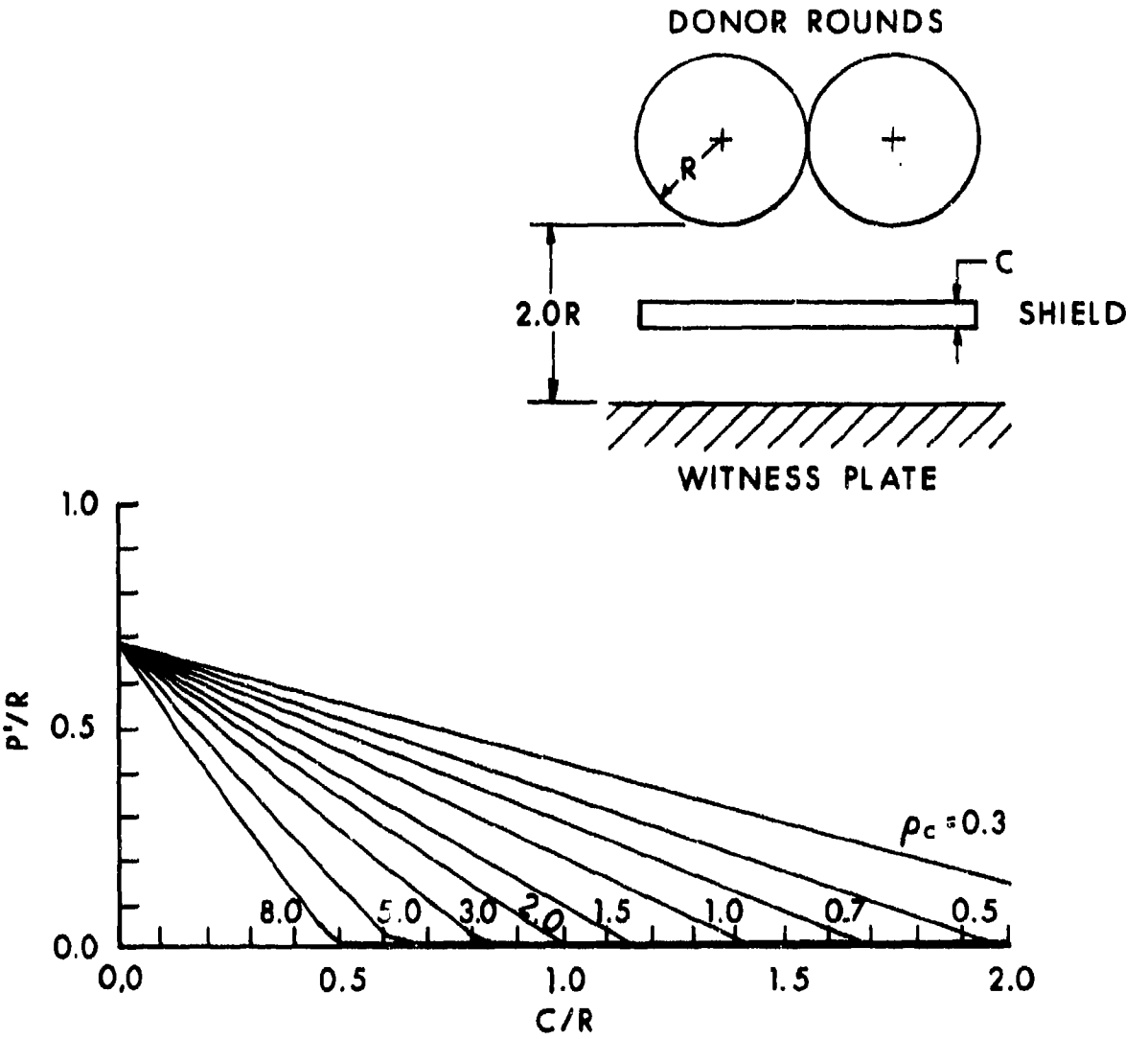

Figure 7. Nondimensional penetration P'/R versus nondimensional shield thickness C/R, where shield is placed at midpoint between donor and acceptor rounds separated by 2.0 R. Shield density ρ_c is a parameter for the family of curves.

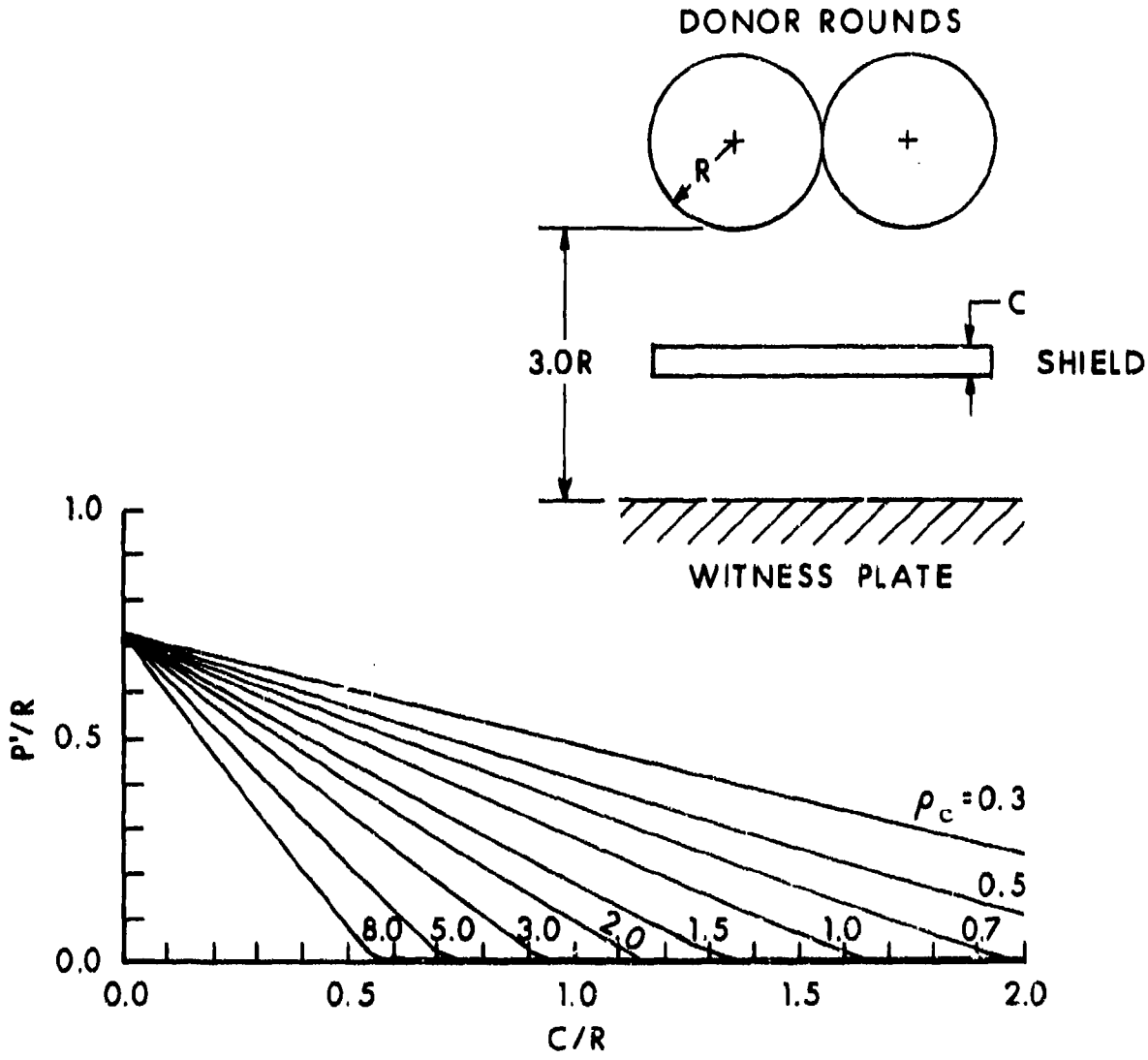

Figure 8. Nondimensional penetration P'/R versus nondimensional shield thickness C/R, where shield is placed at midpoint between donor and acceptor rounds separated by 3.0 R. Shield density ρ_c is parameter for the family of curves.

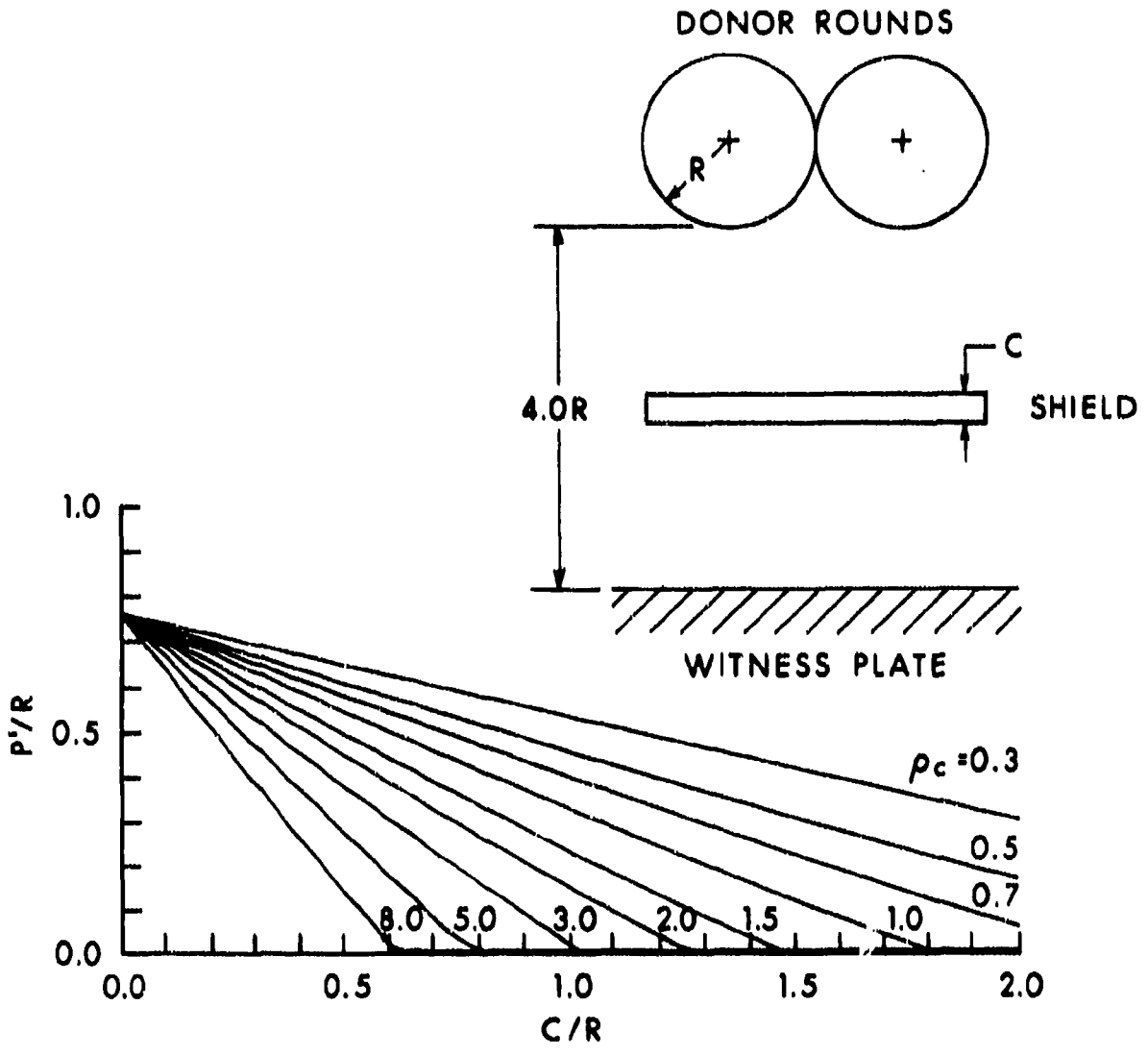

Figure 9. Nondimensional penetration P'/R versus nondimensional shield thickness C/R, where shield is placed at midpoint between donor and acceptor rounds separated by 4.0 R. Shield density ρ_c is parameter for the family of curves.

Figure 10 shows the results obtained for the nondimensional penetration depth as a function of the separation distance D/R for two panels placed symmetrically about the midpoint between the donor and acceptor (or target) rounds. The result is obtained for several densities and for panels 0.53 R thick (this corresponds to panels 1/2" or 1.27 cm thick in the pipe bomb experiments). Separation between donor and acceptor rounds is taken to be 4.0 R in these calculations. These curves show that the penetration versus separation distance drops as the separation increases. This is easily understood as an effect of jet elongation with travel distance. As a result, it is concluded that for a fixed amount of buffer material it is better to separate the material into two panels placed close to or against the shells. Figures 11-14 incorporate the optimum shield material distribution, i.e., separation of the shield material, into two panels as indicated by the results shown in Fig. 10. Comparison with Figs. 6-9 shows the improvement afforded by such an arrangement of shield material. Note that the curves in Figs. 6-9 give the same value at zero total shield thickness and for shields completely filling the donor-acceptor round gap as the corresponding curves in Figs. 11-14. At points in between, however, the curves in Figs. 11-14 dip below their counterparts in Figs. 6-9. These results show that the improvement noted in Fig. 10 as to the optimum placement of shield material under the symmetry constraint is general.

Figure 15 gives data showing that a further improvement in buffer material efficiency is achieved using a "foam" (a low density material) filling the gap between the shells. The curve gives the penetration as a function of the density of the "foam" buffer filling the entire gap. It is seen that the penetration in the target plate is zero at a density of about 0.21 g/cm^3 for a gap of 4.0R. This is equivalent to a 1.05 R thick panel of density 0.80 g/cm^3 which placed at the midpoint will not protect the target plate (penetration P'/R=0.15); divided into two 0.525 R thick panels the penetration is P'/R=0.13. Therefore, the best panel design appears to be a low density "foam" filling the available gap.

VIII. COMPARISON WITH EXPERIMENTAL RESULTS

An extensive series of shield tests using 4.82 cm (1.9") diameter pipe bombs has been run employing a wide variety of shields. The data obtained in these tests has been used to validate the "Main" code. Figure 16 shows a comparison between the experimental and theoretical code results. In Fig. 16 the penetration depth (maximum depth in the target plate) is used for the ordinate while the individual test code numbers (these are the same code numbers used to designate the tests in Ref. 4) are listed along the abscissa. The order of the tests listed along the abscissa is not important. As listed, however, they imply a decreasing function of penetration with increasing shield material. Beneath each entry is a small picture indicating the test arrangement of the shield along with the shield thickness in mm together with symbols indicating shield materials used. Additional test details may be found in Ref. 4. All tests employed Comp B filled 4.82 cm diameter pipe bombs 15 cm in length placed 4 radii above a steel witness plate. The reference case shows the results for no shield between the two pipe bombs and the witness plate. The error bars (obtained from the test data for three shots) indicate the considerable variability of the results obtained in these tests.

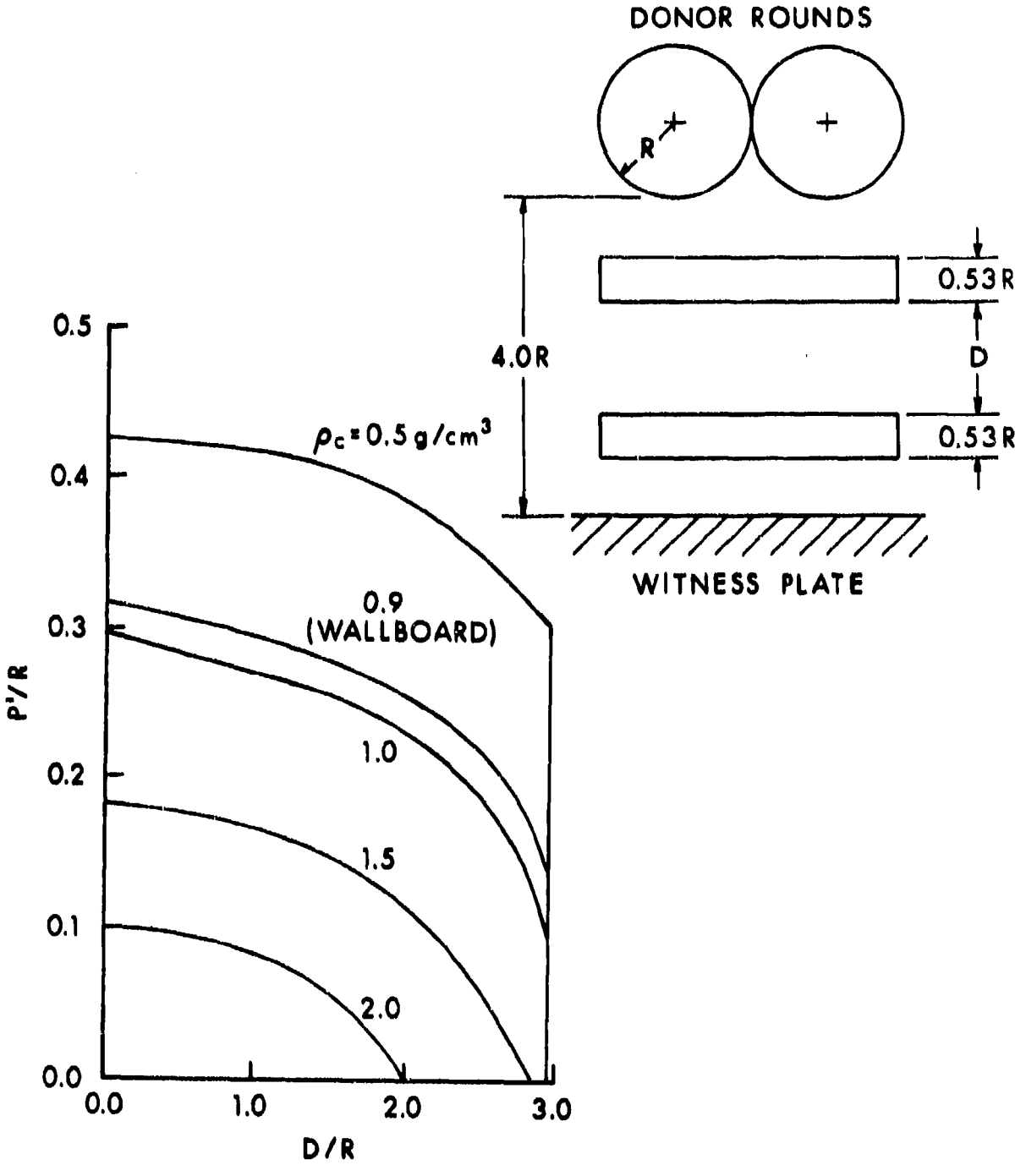

Figure 10. Nondimensional penetration P'/R versus nondimensional panel separation distance D/R for two symmetrically placed 0.53 R thick panels in a 4.0 R space between donors and target plate for various panel densities. The inset shows the geometry. These results indicate that if symmetry must be maintained in packaging, the best placement of shield material is midway between donor and acceptor rounds.

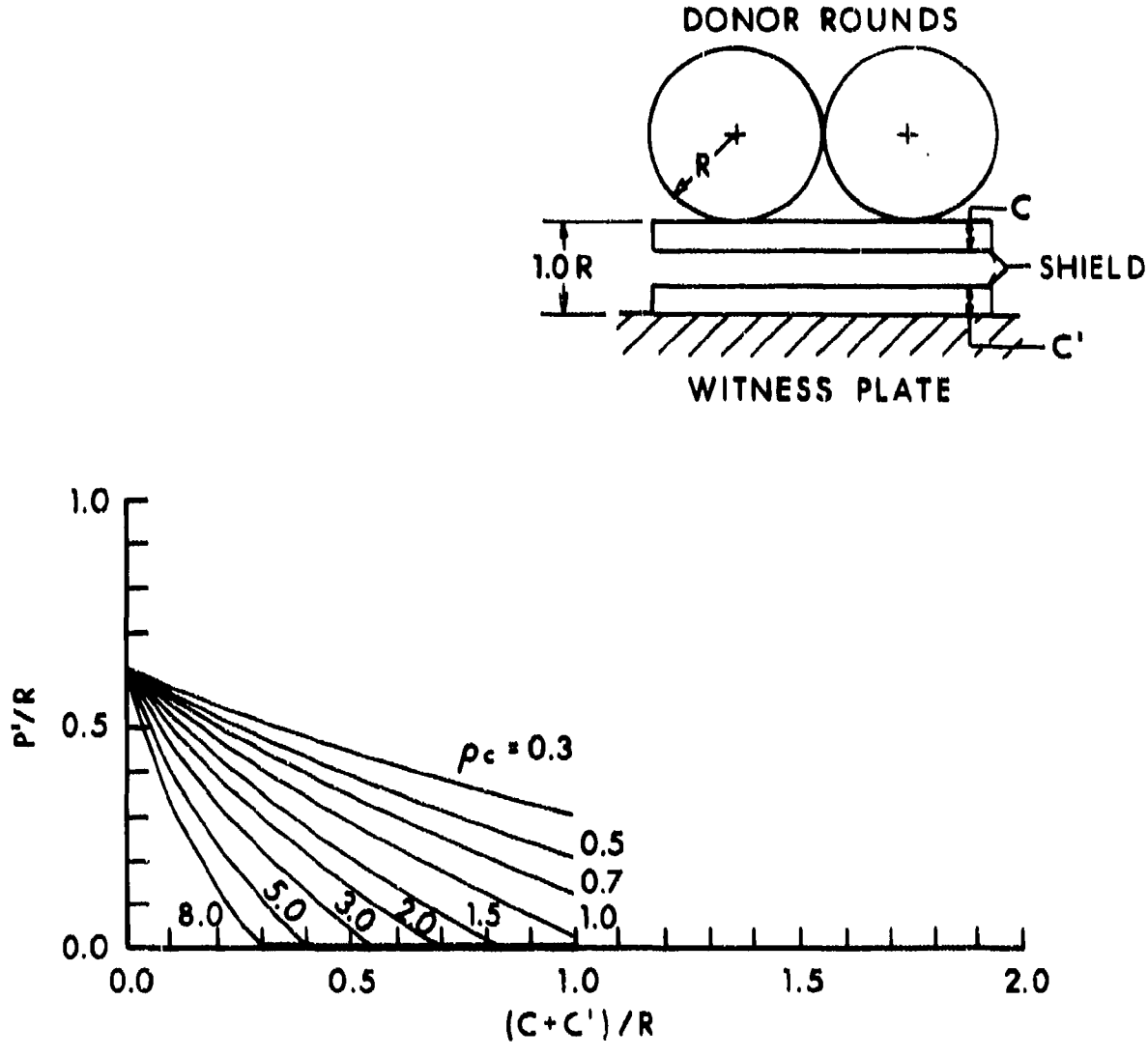

Figure 11. Nondimensional penetration P'/R versus nondimensional total shield thickness (C + C')/R, where the shield consists of two panels symmetrically placed about the midpoint, one against the donor rounds, one against the acceptor rounds (or witness plate, as shown in the inset). Donor-acceptor separation is 1.0 R. Shield density ρ_c is parameter for curves.

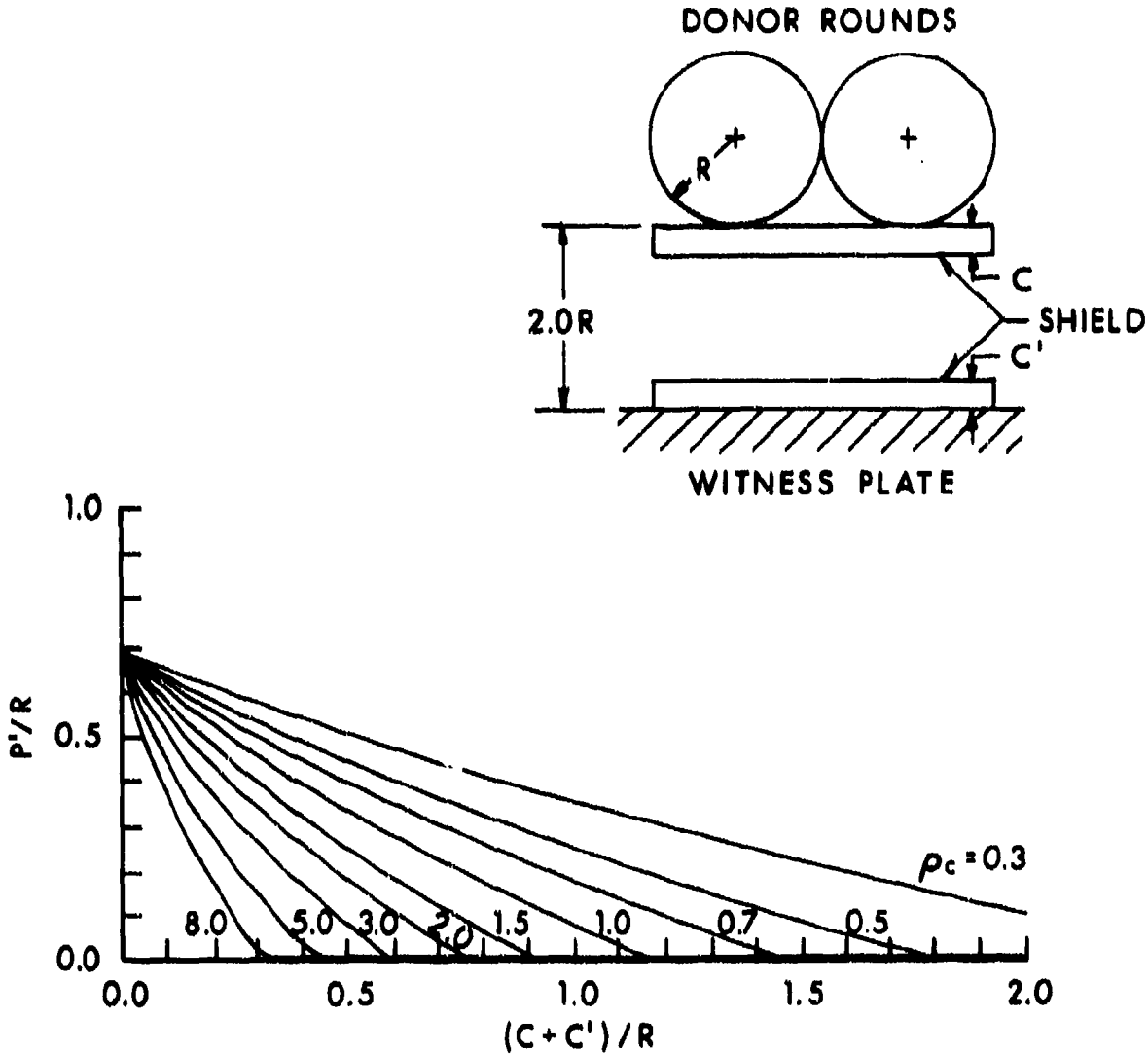

Figure 12. Nondimensional penetration P'/R versus nondimensional total shield thickness (C + C')/R, where the shield consists of two panels symmetrically placed about the midpoint, one against the donor rounds, one against the acceptor rounds (or witness plate as shown in inset). Donor-acceptor separation is 2.0 R. Shield density ρ_c is parameter for curves.

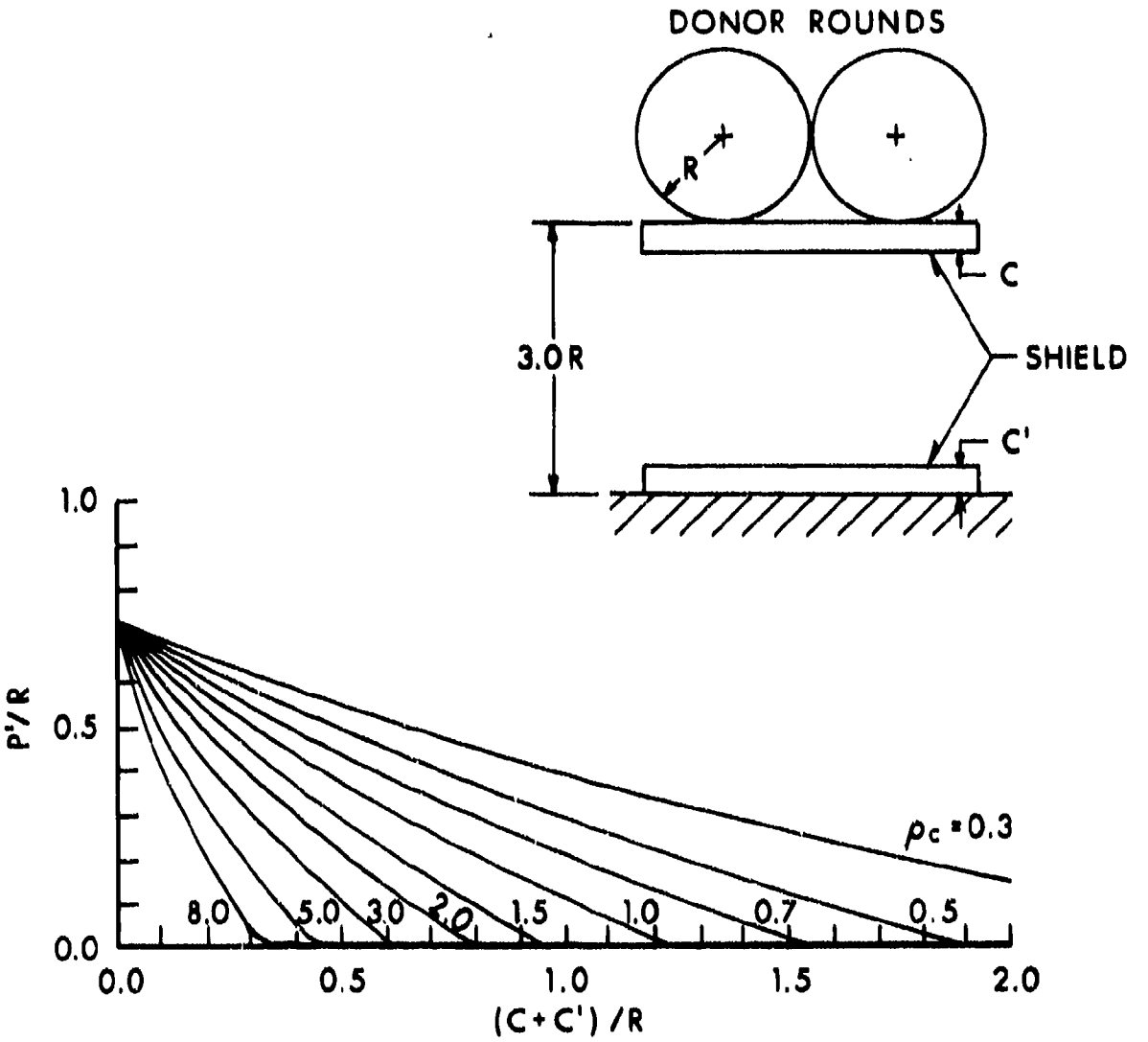

Figure 13. Nondimensional penetration P'/R versus nondimensional total shield thickness (C + C')/R, where the shield consists of two panels symmetrically placed about the midpoint, one against the donor rounds, one against the acceptor rounds (or witness plate, as shown in inset). Donor-acceptor separation is 3.0 R. Shield density ρ_c is parameter for curves.

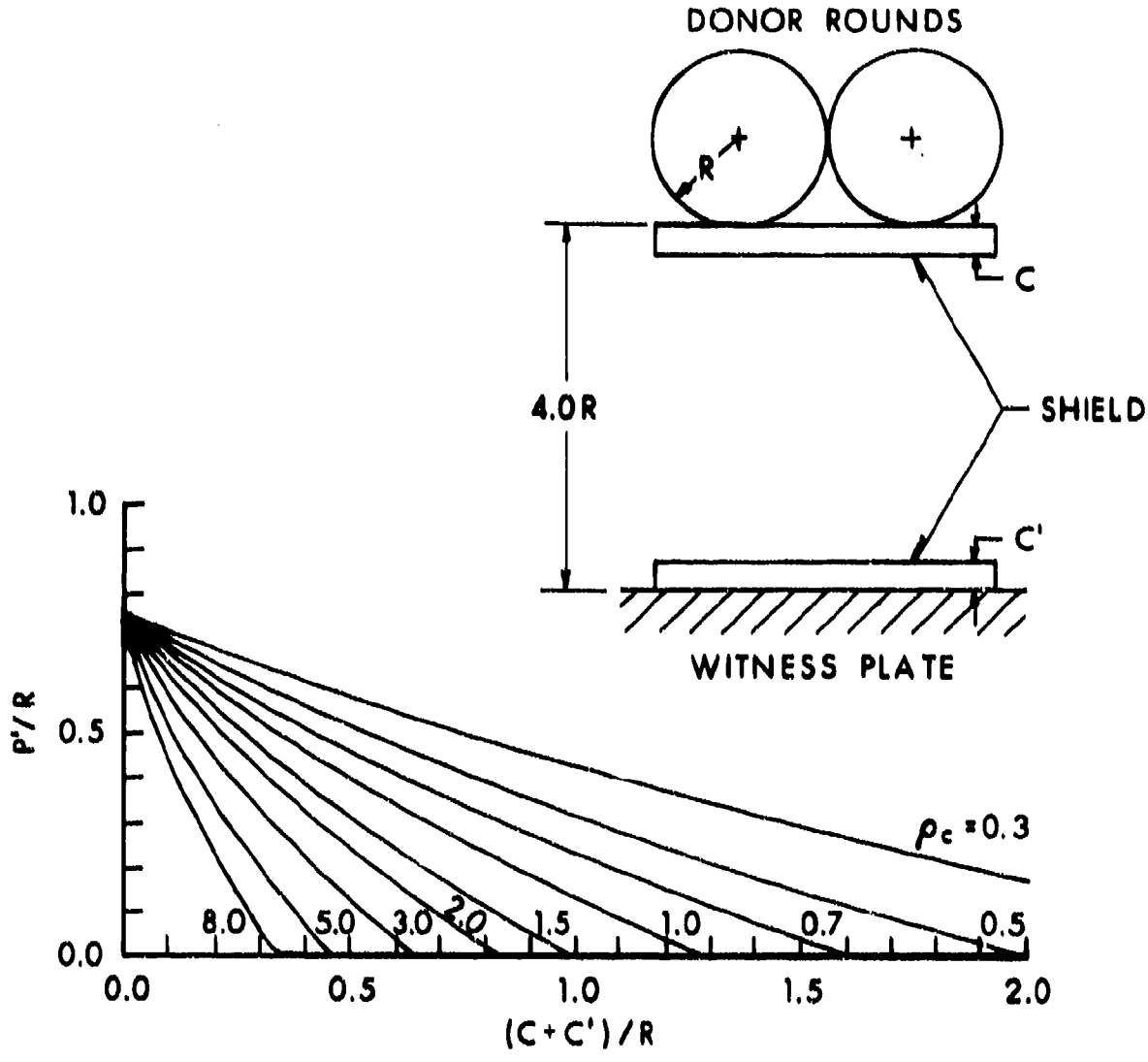

Figure 14. Nondimensional penetration P'/R versus nondimensional total shield thickness (C + C')/R, where the shield consists of two panels symmetrically placed about the midpoint, one against the donor rounds, one against the acceptor rounds (or witness plate as shown in inset). Donor-acceptor separation is 4.0 R. Shield density ρ_c is parameter for curves.

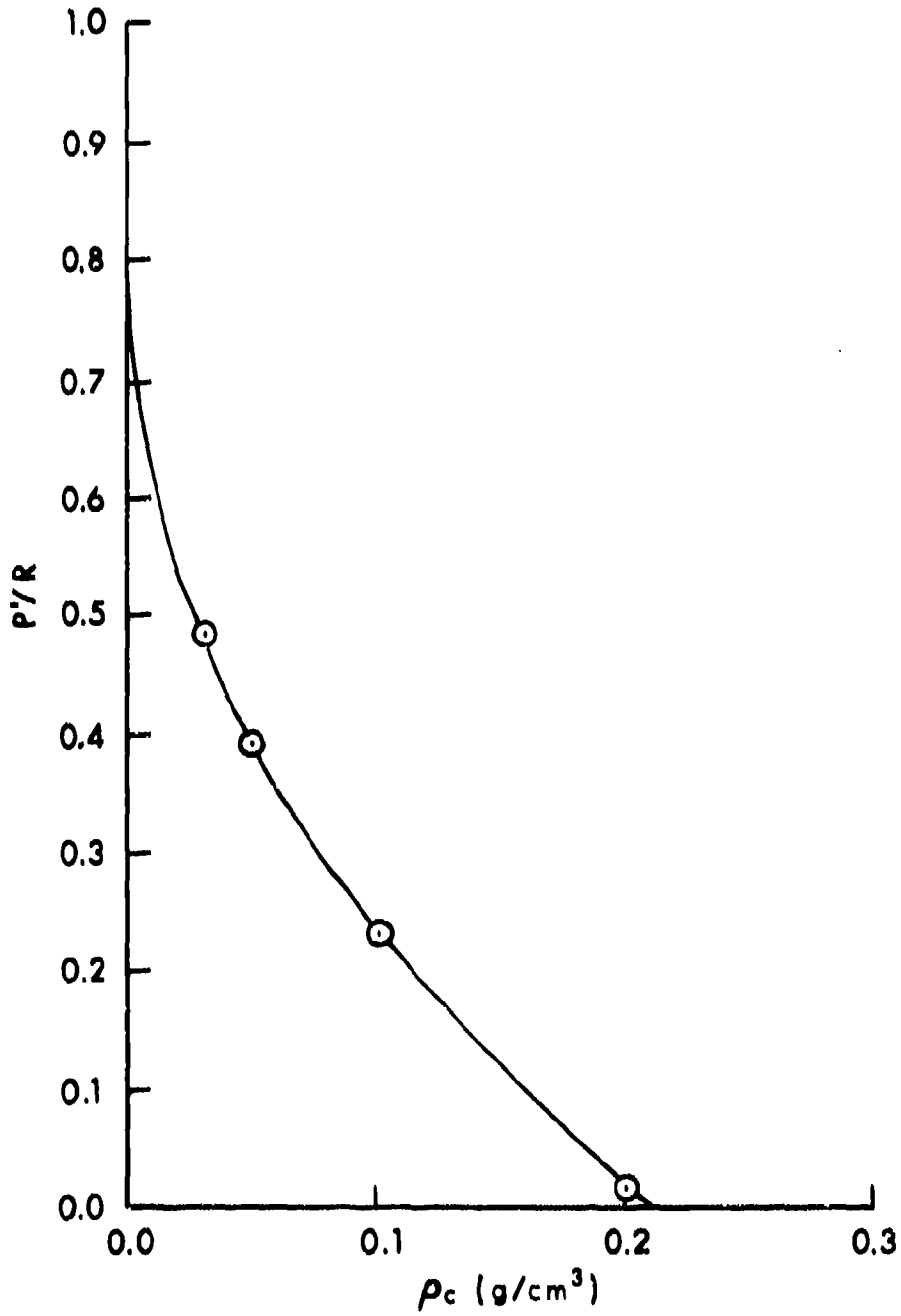

Figure 15. Nondimensional penetration versus density of shield material for a "foam" filling the space between the donor rounds and target plate (acceptor rounds) for a gap of 4.0 R.

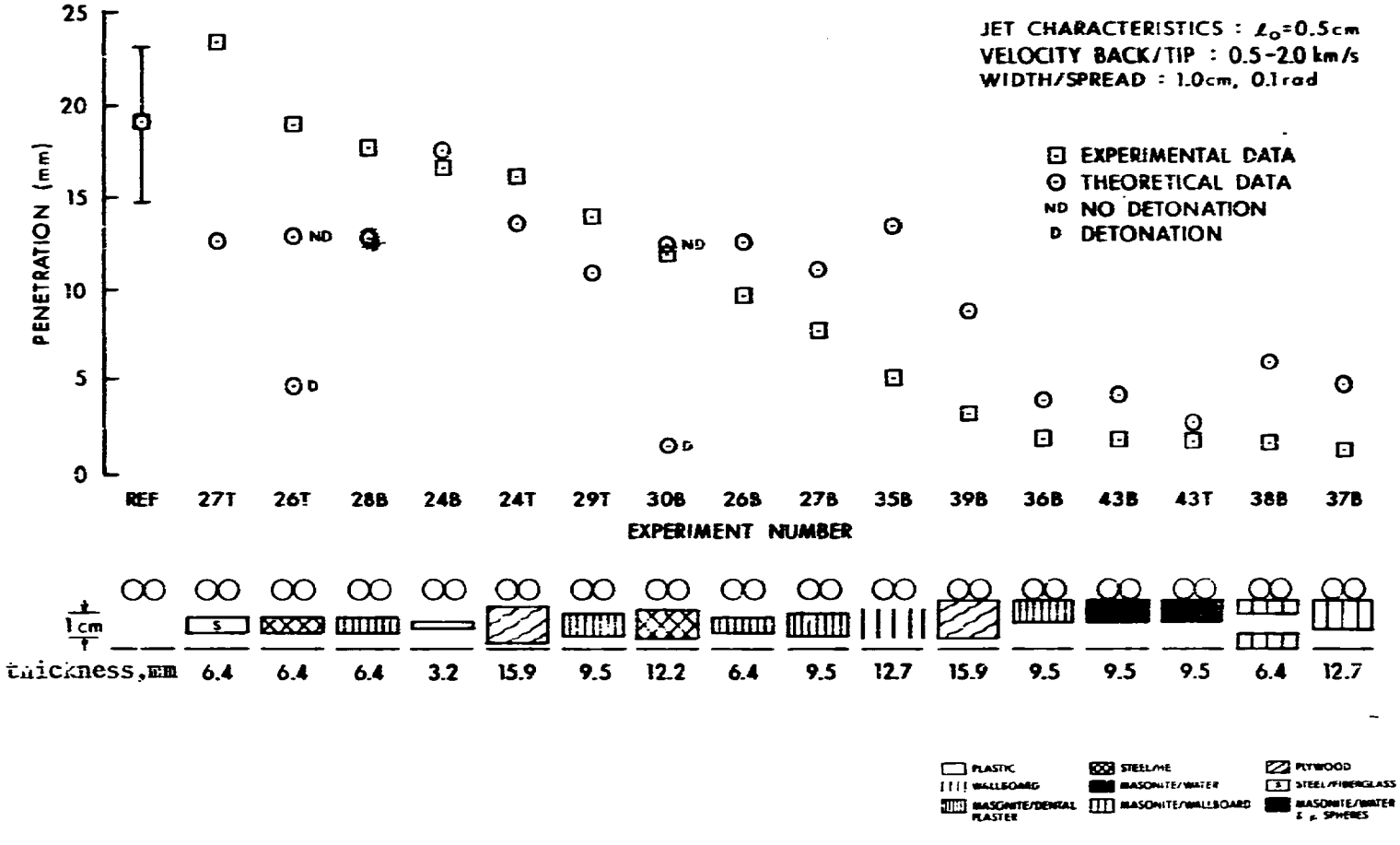

Figure 16. Penetration depth in mm charted for the several experimental shield tests. Theoretical and experimental data points have been plotted for all pipe bomb tests having bombs in contact 4.0 R above the witness plate. Schematics of each test shot with shield thickness, position and composition notes are shown below shot number. Note the error bars on the reference (no shield) test indicating the variablity of the test results. Within these limits agreement between the experimental and theoretical results is good. Note also that the data trend is an artifact of the ordering of test shot data. As expected from theory, the smallest penetrations occurred for shields placed against donor rounds.

In tests 26T and 30B Detasheet was employed between thin sheets of steel to form the shield. The code computed shielding assuming both detonation of the Detasheet and no detonation. The results assuming no detonation are seen to agree satisfactorily with the observed results. At the right side of Fig. 16 are located all the tests in which a shield panel is placed against the donor rounds. It will be noticed that these six tests yielded the best shielding (least penetration into the witness plate) results. This is in general agreement with the predictions of the code as indicated by the results in Fig. 10. Overall the theoretical results given by the code correspond well with the experimental results in Fig. 16. (The reader should keep in mind that in some cases the penetration data is a measurement taken for two or three fragment craters in the witness plate that may be no more than 2-3 mm in diameter.) The experimental data must be regarded as having significant error bars reflecting the variability of these test results. Within these limitations, therefore, the model works well.

The results obtained in matching the experimental and theoretical data indicated that the effects observed were due to the mass column of shield material, and placement of that material alone. The code indicated no significant effect due to the use of hydrates in the shield. Several shots to test this hypothesis have been carried out by G. Gibbons[4]. In these shots equal mass columns of steel, aluminum, plaster, and water were used as shields. Damage to the witness plates was almost identical in these four shots, although in the shot using steel for the shield, the shield material itself produced some pitting in the witness plate (these pits were located to either side of the area usually damaged by the jet from the donor rounds).

IX. CONCLUSIONS

If two neighboring artillery shells in an ammunition pallet are simultaneously detonated, a high velocity metal jet is formed that can detonate other neighboring shells, even if these shells are protected by a significant thickness of armor (for example 15 cm of armor can be penetrated by the jet from two simultaneously detonated 155 mm HE artillery rounds). Equations to model the interaction of shield panels with such jets have been derived and employed to write a computer code to calculate penetration depth of the jet after passing through up to two panels consisting of sandwiches of up to three layers of material. In the code one layer in each panel (the middle layer in three layer panels) can consist of an explosive or a hydrated material that may be activated to yield enhanced pressures under the shock loading of the jet.

Computations using the code have indicated:

(1) The primary effect produced by inert or hydrated materials depends on the mass column of material in the panel and panel placement. Water of hydration produces only minor effects.

(2) The optimum placement for the shield panel to suppress jets is against the donor shells.

(3) Under symmetry requirements (i.e., where all shells must be equally shielded) the best placement employs two shields of equal thickness, one against the donor, one against the acceptor rounds.

(4) Use of explosive material sandwiched in the shields can significantly enhance the effectiveness of the shields. (Such material, however, may enhance impact shock initiation.)

(5) The best symmetric shield design (minimum weight basis) for inhibiting fratricide jets would employ a single panel filling the entire available space between donor and acceptor rounds with the lowest density material capable of inhibiting the jet (as given by the curves in Figs. 6-9) in the available space.

ACKNOWLEDGEMENTS

I would like to thank Gould Gibbons, Jr. of the EEB, TBD for furnishing much of the data used to compare the theoretical calculations with experimental results. I would also like to thank Toni Dorsey for extensive assistance in developing and exercising the computer code "Main." Finally, I wish to acknowledge Dr. Philip M. Howe for proposing this research problem and for his constructive suggestions regarding this task.

APPENDIX

PROGRAM "MAIN"

```
      PROGRAM MAIN(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT,TAPE9)          MAIN      2
      DIMENSION GG(20), DD(20), RRHO(20)                                 MAIN      3
      DIMENSION LAB(4), PLC(50), PLPP(50)                                MAIN      4
C                                                                        MAIN      5
C *** FORMATS                                                            MAIN      6
C                                                                        MAIN      7
    1 FORMAT('   GAP =',E11.4,/)                                        MAIN      8
    2 FORMAT(3X,'ICC = ',I10,4X,'PLC =',E11.4,3X,'PLPP =',E11.4,//)      MAIN      9
    4 FORMAT(A10)                                                        MAIN     10
    5 FORMAT(A10,10X,'LL =',I5)                                          MAIN     11
   10 FORMAT(1H1)                                                        MAIN     12
   15 FORMAT(1HO)                                                        MAIN     13
   20 FORMAT(8E10.3)                                                     MAIN     14
   25 FORMAT(I5)                                                         MAIN     15
   30 FORMAT(4X,'A =',E11.4,6X,'B =',E11.4,3X,'BP =',E11.4,5X,'AP =',E11 MAIN     16
     1.4,6X,'C =',E11.4,5X,'CP =',E11.4,/,4X,'D =',E11.4,' RADIUS =',E11 MAIN     17
     2.4,6X,'H =',E11.4,5X,'HP =',E11.4,5X,'AL =',E11.4,3X,'RHOZ =',E11. MAIN     18
     34,/,4X,'E =',E11.4,5X,'VT =',E11.4,5X,'VB =',E11.4,2X,'ALPHA =',E1 MAIN     19
     41.4,3X,'RHOT =',E11.4,3X,'RHOA =',E11.4,/,1X,'RHOB =',E11.4,3X,'RH MAIN     20
     50C =',E11.4,2X,'RHOAP =',E11.4,2X,'RHOBP =',E11.4,2X,'RHOCP =',E11 MAIN     21
     6.4,6X,'G =',E11.4,/,3X,'VS =',E11.4,5X,'AK =',E11.4,5X,'HF =',E11. MAIN     22
     74,/)                                                               MAIN     23
   40 FORMAT(5X,'P =',E11.4,5X,'C1 =',E11.4,3X,'BETA =',E11.4)           MAIN     24
   50 FORMAT(1H ,' CAPL =',E11.4,5X,'PA =',E11.4,5X,'PB =',E11.4,5X,'PC  MAIN     25
     1=',E11.4,5X,'V1 =',E11.4,3X,'RHOP =',E11.4,/,'  RHO1 =',E11.4,2X,' MAIN     26
     2RHOJ1 =',E11.4,3X,'PRES =',E11.4)                                  MAIN     27
   60 FORMAT(5X,'F =',E11.4,5X,'Y1 =',E11.4,2X,'DELY1 =',E11.4,5X,'P2 =' MAIN     28
     1,E11.4,' DELL1P =',E11.4)                                          MAIN     29
   62 FORMAT('  RHO2 =',E11.4)                                          MAIN     30
   70 FORMAT(3X,'PBP =',E11.4,5X,'BP =',E11.4,' DELLBP =',E11.4)         MAIN     31
   80 FORMAT(4X,'Y2 =',E11.4,5X,'V2 =',E11.4,3X,'PRES =',E11.4,6X,'F =', MAIN     32
     1E11.4,2X,'DELY2 =',E11.4,5X,'P4 =',E11.4,/,' DELL2P =',E11.4,5X,'F MAIN     33
     2P =',E11.4)                                                        MAIN     34
   82 FORMAT(1H ,'DELLA =',E11.4,'  DELLB =',E11.4,'  DELLC =',E11.4)    MAIN     35
   90 FORMAT(4X,'PP =',E11.4,2X,'DELL1 =',E11.4,' DELL1P =',E11.4,2X,'DE MAIN     36
     1LL2 =',E11.4,' DELL2P =',E11.4,3X,'PPIN =',E11.4)                  MAIN     37
   92 FORMAT(1H ,'DELL1 =',E11.4)                                        MAIN     38
   94 FORMAT(3X,'PCP =',E11.4,5X,'CP =',E11.4,' DELLCP =',E11.4)         MAIN     39
   96 FORMAT(3X,'PAP =',E11.4,5X,'AP =',E11.4,' DELLAP =',E11.4,2X,'DELL MAIN     40
     12 =',E11.4)                                                        MAIN     41
   98 FORMAT(' RHOPP =',E11.4,2X,'RHOJ2 =',E11.4,5X,'V2 =',E11.4)       MAIN     42
C                                                                        MAIN     43
C *** CALCULATIONS                                                       MAIN     44
C                                                                        MAIN     45
      CVH2O = 2.007E7 $ CV = 8.78E6 $ VDET = 7.0E5                       MAIN     46
      WRITE(6,10)                                                        MAIN     47
      BX = 1.0 $ BY = 1.0                                                MAIN     48
      LAB(1) = 10H TONIHMA  $ LAB(2) = 10H X5742-309                     MAIN     49
      LAB(3) = 10H      PLOT $ LAB(4) = 10H SCOOP                        MAIN     50
      XPAGE = 8.0 $ YPAGE = 8.0                                          MAIN     51
      CALL PLTBEG(XPAGE,YPAGE,1.0,9,LAB)                                 MAIN     52
      CALL PLOT(BX,BY,-3)                                                MAIN     53
      BX = 0.0 $ BY = 0.0                                                MAIN     54
      CALL FACTOR(0.5)                                                   MAIN     55
C     DO 3000 IC = 1,2                                                   MAIN     56
      DO 3000 IC = 2,2                                                   MAIN     57
      READ(5,20) A, B, BP, AP, CP, RADIUS, HP, AL, RHOZ, E, VT, VB,      MAIN     58
     1 ALPHA, RHOT, VS, AK, HF                                           MAIN     59
      A = 0.0 $ B = 0.0 $ AP = 0.0 $ BP = 0.0 $ CP = 0.0 $ HP = 0.0      MAIN     60
      RADIUS = 1.0 $ AL = 0.20 $ E = 0.40                                MAIN     61
      READ(5,25) ICOUNT                                                  MAIN     62
      READ(5,4) TITLE                                                    MAIN     63
      DO 700 LL = 1,ICOUNT                                               MAIN     64
```

```
      WRITE(6,5) TITLE, LL                                                    MAIN      65
      WRITE(6,15)                                                             MAIN      66
      READ(5,20) C, D, H, RHOA, RHOB, RHOC, RHOAP, RHOBP, RHOCP, G            MAIN      67
      READ(5,20) (GG(I),I=1,2)                                                MAIN      69
      READ(5,20) (RRHO(I),I=1,9)                                              MAIN      70
      DO 680 IG = 1,2                                                         MAIN      71
      G = GG(IG)                                                              MAIN      72
      DO 670 ID = 1,4                                                         MAIN      73
      CALL AXIS(0.0,0.0,4HC+CP,-4,10.0,0.0,0.0,0.2)                           CORRB      1
      CALL AXIS(0.0,0.0,2HPP,2,10.0,90.0,0.0,0.2)                             MAIN      75
      GAP = FLOAT(ID)                                                         MAIN      76
      DO 660 IRHO = 1,9                                                       MAIN      78
      RHOC = RRHO(IRHO)                                                       MAIN      79
      RHOCP = RHOC                                                            CORRB      2
      IPCC = 0                                                                MAIN      80
      DO 655 ICC = 1,41                                                       MAIN      81
      C = (ICC-1) * 2.0 / 40.0                                                MAIN      82
      IF(C .EQ. 0.0) C = 0.001                                                MAIN      83
      IF(C .GT. GAP) GO TO 655                                                MAIN      84
      C = C / 2.0 $ CP = C                                                    CORRB      3
      D = GAP - C - CP                                                        CORRB      4
      H = 0.0 $ HP = 0.0                                                      CORRB      5
      RHOA = 0.0 $ RHOAP = 0.0 $ RHOB = 0.0 $ RHOBP = 0.0                     MAIN      86
      IF(G .EQ. 0.209) HF = 5.762E9                                           MAIN      87
      IF(G .EQ. 0.290) HF = 5.084E9                                           MAIN      88
      IF(G .EQ. 1.0) HF = 3.333E9                                             MAIN      89
      IF(G .EQ. 0.260) HF = 3.33E9                                            MAIN      90
      IF(IC .EQ. 2) HP = H                                                    MAIN      91
      CAPL = RADIUS + H + A + B + C + D + AP + BP + CP + HP                   MAIN      95
      C1 = (VT-VB) / (AL*VB)                                                  MAIN      96
      P = 0.0                                                                 MAIN      97
      DX = AL / 100.0                                                         MAIN      98
      X = DX / 2.0                                                            MAIN      99
      DO 100 I = 1,99                                                         MAIN     100
      IF(RHOZ .EQ. 0.0 .OR. RHOT .EQ. 0.0) GO TO 150                          MAIN     101
      P = P + (SQRT(RHOZ/RHOT)) * DX * (1.0+(C1*CAPL+C1*P)/(1.0+C1*X))**      MAIN     102
     10.5/(1.0+ALPHA*CAPL/E) ** 0.5                                           MAIN     103
      X = X + DX                                                              MAIN     104
  100 CONTINUE                                                                MAIN     105
C 150 WRITE(6,40) P, C1, BETA                                                 MAIN     106
  150 CONTINUE                                                                MAIN     107
      CAPL1 = H + A + C / 2.0                                                 MAIN     108
      PA = 0.0                                                                MAIN     109
      DX = AL / 100.0                                                         MAIN     110
      X = AL - DX / 2.0                                                       MAIN     111
      DO 200 I = 1,99                                                         MAIN     112
      IF(RHOZ .EQ. 0.0 .OR. RHOA .EQ. 0.0) GO TO 210                          MAIN     113
      PA = PA + (SQRT(RHOZ/RHOA))*DX*(1.0+(C1*H+C1*PA)/(1.0+C1*X))**0.5/      MAIN     114
     1 (1.0+ALPHA*H/E) ** 0.5                                                 MAIN     115
      X = X - DX                                                              MAIN     116
      IF(PA .GE. A) GO TO 210                                                 MAIN     117
  200 CONTINUE                                                                MAIN     118
  210 DELLA = AL - X                                                          MAIN     119
      PC = 0.0                                                                MAIN     120
      BETA = 1.0                                                              MAIN     121
      CAPVS = 5.0E5                                                           MAIN     122
      DX = (AL-DELLA) / 100.0                                                 MAIN     123
      X = (AL-DELLA) - DX / 2.0                                               MAIN     124
      DO 220 I = 1,99                                                         MAIN     125
      IF(RHOC .EQ. 0.0) GO TO 1050                                            MAIN     126
C                                                                             MAIN     127
C *** NEGATIVE BETA FOR DETONATION LAYER.                                     MAIN     128
C *** INCLUDES PRESSURE DROP WITH EXPANSION.                                  MAIN     129
C                                                                             MAIN     130
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      IF(G .LT. 0.0) BETA = 1.0 - G * (C/(C+PC*VDET/CAPVS)) / (0.5*RHOC*  MAIN      131
     1RHOZ*VT*VT/((SQRT(RHOC)+SQRT(RHOZ))**2))                            MAIN      132
      IF(BETA .LT. 0.0) BETA = 0.0                                        MAIN      133
      IF(G .LT. 0.0) GO TO 1050                                           MAIN      134
      RHOJ = RHOZ * E / ((E+ALPHA*(H+A+C))*(1.0+C1*(H+A+PC)/(1.0+C1*X)))  MAIN      135
      RO = RHOJ / RHOC                                                    MAIN      136
      VJ = VB + (VT-VB) * X / AL                                          MAIN      137
      CAPVS = VJ / (1.0+SQRT(RHOC/RHOJ))                                  MAIN      138
      DGREEK = 2.0 * G * HF / CAPVS**2                                    MAIN      139
      AKK = 1.0                                                           MAIN      140
      IF(G .GT. 0.0) AKK = 1.0 / (1.0+(1.0-G)*CV/(G*CVH2O))               MAIN      141
C     IF(G .EQ. 1.0) GO TO 1000                                           MAIN      142
      TEMP = (0.5*RHOJ*RHOC*VJ*VJ/(2.0*(SQRT(RHOJ)+SQRT(RHOC))**2)) / ((  MAIN      143
     11.0-G)*CV)                                                          MAIN      144
      IF(TEMP .LT. 373.0) GO TO 1000                                      MAIN      145
      GO TO 1010                                                          MAIN      146
 1000 TEMP = 373.0                                                        MAIN      147
 1010 WORKEF = (TEMP-373.0) / TEMP                                        MAIN      148
      GAM = WORKEF * AKK                                                  MAIN      149
      TFAC = 1.0 - (GAM/RO) * (1.0-GAM/RO) * (1.0-DGREEK)                 MAIN      150
      IF(TFAC .LE. 0.0) GO TO 1030                                        MAIN      151
      GO TO 1040                                                          MAIN      152
 1030 BETA = 1.0                                                          MAIN      153
      GO TO 1050                                                          MAIN      154
 1040 V = (1.0-SQRT(TFAC)) / (1.0-GAM/RO)                                 MAIN      155
      FRHO = SQRT(RO)                                                     MAIN      156
      FRHO = (FRHO*FRHO+FRHO-1.0) / (1.0+FRHO)                            MAIN      157
      BETA = 1.0 / (1.0+GAM*(V*V*FRHO-DGREEK))                            MAIN      158
      IF(BETA .LT. 0.0) BETA = 0.0                                        MAIN      159
 1050 RHO1 = BETA * RHOC                                                  MAIN      160
      IF(RHO1 .LT. RHOC) RHO1 = RHOC                                      MAIN      161
      IF(RHOZ .EQ. 0.0 .OR. RHO1 .EQ. 0.0) GO TO 230                      MAIN      162
      PC = PC + (SQRT(RHOZ/RHO1)) * DX * (1.0+(C1*(H+A+PC))/(1.0+C1*X))   MAIN      163
     1**0.5 / (1.0+ALPHA*(H+A)/E) ** 0.5                                  MAIN      164
      X = X - DX                                                          MAIN      165
      IF(PC .GE. C) GO TO 230                                             MAIN      166
  220 CONTINUE                                                            MAIN      167
  230 DELLC = AL - DELLA - X                                              MAIN      168
      PB = 0.0                                                            MAIN      169
      DX = (AL-DELLA-DELLC) / 100.0                                       MAIN      170
      X = (AL-DELLA-DELLC) - DX / 2.0                                     MAIN      171
      DO 240 I = 1,99                                                     MAIN      172
      IF(RHOZ .EQ. 0.0 .OR. RHOB .EQ. 0.0) GO TO 250                      MAIN      173
      PB = PB + (SQRT(RHOZ/RHOB)) * DX * (1.0+(C1*(H+A+C+PB))/(1.0+C1*X)  MAIN      174
     1)**0.5 / (1.0+ALPHA*(H+A+C)/E) ** 0.5                               MAIN      175
      X = X - DX                                                          MAIN      176
      IF(PB .GE. B) GO TO 250                                             MAIN      177
  240 CONTINUE                                                            MAIN      178
  250 DELLB = AL - DELLA - DELLC - X                                      MAIN      179
      DELL1 = DELLA + DELLB + DELLC                                       MAIN      180
C     WRITE(6,92) DELL1                                                   MAIN      181
C     WRITE(6,82) DELLA, DELLB, DELLC                                     MAIN      182
      RHOJ1 = RHOZ * E / ((1.0+C1*(H+A+B+C)/(1.0+C1*(AL-DELL1))) * (E+AL  MAIN      183
     1PHA*(AL-DELL1)))                                                    MAIN      184
      E1 = E / (1.0+ALPHA*(H+A+B+C)/E)                                    MAIN      185
      QCOL = AK * E1 * RHOJ1                                              MAIN      186
      RCOL = RHOB * B                                                     MAIN      187
      DISS = B                                                            MAIN      188
      DIS = B                                                             MAIN      189
      RHOP = RHOB                                                         MAIN      190
      IF(QCOL .LE. RCOL) GO TO 260                                        MAIN      191
      RCOL = RCOL + RHOC * C                                              MAIN      192
      DISS = DISS + C                                                     MAIN      193
      DIS = C                                                             MAIN      194
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      RHOP = RHOC                                                       MAIN      195
      IF(QCOL .LE. RCOL) GO TO 260                                      MAIN      196
      RCOL = RCOL + RHOA * A                                            MAIN      197
      DISS = DISS + A                                                   MAIN      198
      DIS = A                                                           MAIN      199
      RHOP = RHOA                                                       MAIN      200
      IF(QCOL .LE. RCOL) GO TO 260                                      MAIN      201
      IF(A+B+C .EQ. 0.0) GO TO 253                                      MAIN      202
      RHOP = RCOL / (A+B+C)                                             MAIN      203
      GO TO 255                                                         MAIN      204
  253 RHOP = 0.0                                                        MAIN      205
  255 GO TO 270                                                         MAIN      206
  260 IF(RCOL .EQ. 0.0) GO TO 265                                       MAIN      207
      FF = (QCOL-RCOL) / RCOL                                           MAIN      208
      GO TO 267                                                         MAIN      209
  265 FF = 0.0                                                          MAIN      210
  267 RCOL = RCOL - RHOP * DIS * FF                                     MAIN      211
      DISS = DISS - DIS * FF                                            MAIN      212
      IF(DISS .EQ. 0.0) GO TO 268                                       MAIN      213
      RHOP = RCOL / DISS                                                MAIN      214
      GO TO 270                                                         MAIN      215
  268 RHOP = 0.0                                                        MAIN      216
  270 CONTINUE                                                          MAIN      217
      V1 = VB + (VT-VB) * (1.0-DELL1/AL)                                MAIN      218
      PRES = 0.5 * RHOP * RHOJ1 * V1 * V1 / (SQRT(RHOP)+SQRT(RHOJ1))**2 MAIN      219
C     WRITE(6,50) CAPL, PA, PB, PC, V1, RHOP, RHO1, RHOJ1, PRES         MAIN      220
      F = 1.0 / (1.0+(SQRT(PRES/RHOJ1))/(ALPHA*V1))                     MAIN      221
      IF((A*RHOA+B*RHOB+C*RHO1) .EQ. 0.0) GO TO 274                     MAIN      222
      Y1 = AK * E1 * RHOU1 / (1.0+E1/(A*RHOA+B*RHOB+C*RHO1))            MAIN      223
      GO TO 276                                                         MAIN      224
  274 Y1 = 0.0                                                          MAIN      225
  276 DELY1 = -Y1 * (1.0-SQRT((1.0+ALPHA*D/E)/(1.0+ALPHA*F*D/E)))       MAIN      226
      P2 = 0.0                                                          MAIN      227
      CAPL2 = H + A + B + C + D                                         MAIN      228
      DX = (AL-DELL1) / 100.0                                           MAIN      229
      X = (AL-DELL1) - DX / 2.0                                         MAIN      230
      DO 300 I = 1,99                                                   MAIN      231
      P2 = P2 + DX * (1.0+C1*CAPL2/(1.0+C1*X))                          MAIN      232
      X = X - DX                                                        MAIN      233
      IF(P2 .GE. DELY1) GO TO 310                                       MAIN      234
  300 CONTINUE                                                          MAIN      235
  310 DELL1P = AL - DELL1 - X                                           MAIN      236
C     WRITE(6,60) F, Y1, DELY1, P2, DELL1P                              MAIN      237
C     WRITE(6,62) RHO2                                                  MAIN      238
      PBP = 0.0                                                         MAIN      239
      DX = (AL-DELL1-DELL1P) / 100.0                                    MAIN      240
      X = (AL-DELL1-DELL1P) - DX / 2.0                                  MAIN      241
      DO 400 I = 1,99                                                   MAIN      242
      IF(RHOZ .EQ. 0.0 .OR. RHOBP .EQ. 0.0) GO TO 410                   MAIN      243
      PBP = PBP + (SQRT(RHOZ/RHOBP)) * DX * (1.0+(C1*(CAPL2+PBP))/(1.0+C MAIN      244
     1*X)) ** 0.5 / (1.0+ALPHA*CAPL2/E) ** 0.5                          MAIN      245
      X = X - DX                                                        MAIN      246
      IF(PBP .GE. BP) GO TO 410                                         MAIN      247
  400 CONTINUE                                                          MAIN      248
  410 DELLBP = AL - DELL1 - DELL1P - X                                  MAIN      249
C     WRITE(6,70) PBP, BP, DELLBP                                       MAIN      250
      PCP = 0.0                                                         MAIN      251
      BETA = 1.0                                                        MAIN      252
      DX = (AL-DELL1-DELL1P-DELLBP) / 100.0                             MAIN      253
      X = (AL-DELL1-DELL1P-DELLBP) - DX / 2.0                           MAIN      254
      DO 420 I = 1,99                                                   MAIN      255
C                                                                       MAIN      256
C *** NEGATIVE BETA FOR DETONATION LAYER.                               MAIN      257
C *** INCLUDES PRESSURE DROP WITH EXPANSION                             MAIN      258
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C                                                                       MAIN      259
      IF(RHOCP .EQ. 0.0) GO TO 2050                                     MAIN      260
      IF(G .LT. 0.0) BETA = 1.0 - G * (CP/(CP+PCP*VDET/CAPVS)) / (0.5*  MAIN      261
     1RHOCP*RHOZ*VT*VT/((SQRT(RHOCP)+SQRT(RHOZ))**2))                   MAIN      262
      IF(BETA .LT. 0.0) BETA = 0.0                                      MAIN      263
      IF(G .LT. 0.0) GO TO 2050                                         MAIN      264
      RHOJ = RHOZ * E / ((E+ALPHA*(CAPL2+BP))*(1.0+C1*(CAPL2+BP+PCP)/(1. MAIN      265
     10+C1*X)))                                                         MAIN      266
      RO = RHOJ / RHOCP                                                 MAIN      267
      VJ = VB + (VT-VB) * X / AL                                        MAIN      268
      CAPVS = VJ / (1.0+SQRT(RHOCP/RHOJ))                               MAIN      269
      DGREEK = 2.0 * G * HF / CAPVS**2                                  MAIN      270
      AKK = 1.0                                                         MAIN      271
      IF(G .GT. 0.0) AKK = 1.0 / (1.0+(1.0-G)*CV/(G*CVH2O))             MAIN      272
C     IF(G .EQ. 1.0) GO TO 2000                                         MAIN      273
      TEMP = (0.5*RHOJ*RHOCP*VJ*VJ/(2.0*(SQRT(RHOJ)+SQRT(RHOCP))**2)) / MAIN      274
     1 ((1.0-G)*CV)                                                     MAIN      275
      IF(TEMP .LT. 373.0) GO TO 2000                                    MAIN      276
      GO TO 2010                                                        MAIN      277
 2000 TEMP = 373.0                                                      MAIN      278
 2010 WORKEF = (TEMP-373.0) / TEMP                                      MAIN      279
      GAM = WORKEF * AKK                                                MAIN      280
      TFAC = 1.0 - (GAM/RO) * (1.0-GAM/RO) * (1.0-DGREEK)               MAIN      281
      IF(TFAC .LE. 0.0) GO TO 2030                                      MAIN      282
      GO TO 2040                                                        MAIN      283
 2030 BETA = 1.0                                                        MAIN      284
      GO TO 2050                                                        MAIN      285
 2040 V = (1.0-SQRT(TFAC)) / (1.0-GAM/RO)                               MAIN      286
      FRHO = SQRT(RO)                                                   MAIN      287
      FRHO = (FRHO*FRHO+FRHO-1.0) / (1.0+FRHO)                          MAIN      288
      BETA = 1.0 / (1.0+GAM*(V*V*FRHO-DGREEK))                          MAIN      289
      IF(BETA .LT. 0.0) BETA = 0.0                                      MAIN      290
 2050 RHO2 = BETA * RHOCP                                               MAIN      291
      IF(RHO2 .LT. RHOCP) RHO2 = RHOCP                                  MAIN      292
      IF(RHOZ .EQ. 0.0 .OR. RHO2 .EQ. 0.0) GO TO 430                    MAIN      293
      PCP = PCP + (SQRT(RHOZ/RHO2)) * DX * (1.0+C1*(CAPL2+BP+PCP) / (1.0 MAIN      294
     1+C1*X)) ** 0.5 / (1.0+ALPHA*(CAPL2+BP)/E) ** 0.5                  MAIN      295
      X = X - DX                                                        MAIN      296
      IF(PCP .GE. CP) GO TO 430                                         MAIN      297
  420 CONTINUE                                                          MAIN      298
  430 DELLCP = AL - DELL1 - DELL1P - DELLBP - X                         MAIN      299
C     WRITE(6,94) PCP, CP, DELLCP                                       MAIN      300
      PAP = 0.0                                                         MAIN      301
      DX = (AL-DELL1-DELL1P-DELLBP-DELLCP) / 100.0                      MAIN      302
      X = (AL-DELL1-DELL1P-DELLBP-DELLCP) - DX / 2.0                    MAIN      303
      DO 440 I = 1,99                                                   MAIN      304
      IF(RHOZ .EQ. 0.0 .OR. RHOAP .EQ. 0.0) GO TO 450                   MAIN      305
      PAP = PAP + (SQRT(RHOZ/RHOAP)) * DX * (1.0+C1*(CAPL2+BP+CP+PAP)/(1 MAIN      306
     1.0+C1*X)) ** 0.5 / (1.0+ALPHA*(CAPL2+BP+CP)/E) ** 0.5             MAIN      307
      X = X - DX                                                        MAIN      308
      IF(PAP .GE. AP) GO TO 450                                         MAIN      309
  440 CONTINUE                                                          MAIN      310
  450 DELLAP = AL - DELL1 - DELL1P - DELLBP - DELLCP - X                MAIN      311
      DELL2 = DELLAP + DELLBP + DELLCP                                  MAIN      312
C     WRITE(6,96) PAP, AP, DELLAP, DELL2                                MAIN      313
      V2 = VB + (VT-VB) * (AL-DELL1-DELL1P-DELL2) / AL                  MAIN      314
      IF(AP+BP+CP .EQ. 0.0) GO TO 451                                   MAIN      315
      RHOPP = (AP*RHOAP+BP*RHOBP+CP*RHOCP) / (AP+BP+CP)                 MAIN      316
      GO TO 452                                                         MAIN      317
  451 RHOPP = 0.0                                                       MAIN      318
  452 RHOJ2 = RHOZ * E / (((1.0+C1*(CAPL2+AP+BP+CP)/(1.0+C1*(AL-DELL1-  MAIN      319
     1DELL1P-DELL2)))*(E+ALPHA*(AL-DELL1-DELL1P-DELL2))))               MAIN      320
      E2 = E / (1.0+ALPHA*(CAPL2+AP+BP+CP)/E)                           MAIN      321
      QCOL = AK * E2 * RHOJ2                                            MAIN      322
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```
      RCOL = RHOBP * AP                                                  MAIN      323
      DISS = AP                                                          MAIN      324
      DIS = AP                                                           MAIN      325
      RHOPP = RHOAP                                                      MAIN      326
      IF(QCOL .LE. RCOL) GO TO 460                                       MAIN      327
      RCOL = RCOL + RHOCP * CP                                           MAIN      328
      DISS = DISS + CP                                                   MAIN      329
      DIS = CP                                                           MAIN      330
      RHOPP = RHOCP                                                      MAIN      331
      IF(QCOL .LE. RCOL) GO TO 460                                       MAIN      332
      RCOL = RCOL + RHOAP * AP                                           MAIN      333
      DISS = DISS + AP                                                   MAIN      334
      DIS = AP                                                           MAIN      335
      RHOPP = RHOBP                                                      MAIN      336
      IF(QCOL .LE. RCOL) GO TO 460                                       MAIN      337
      IF(AP+BP+CP .EQ. 0.0) GO TO 453                                    MAIN      338
      RHOPP = RCOL / (AP+BP+CP)                                          MAIN      339
      GO TO 455                                                          MAIN      340
  453 RHOP = 0.0                                                         MAIN      341
  455 GO TO 470                                                          MAIN      342
  460 IF(RCOL .EQ. 0.0) GO TO 465                                        MAIN      343
      FF = (QCOL-RCOL) / RCOL                                            MAIN      344
      GO TO 467                                                          MAIN      345
  465 FF = 0.0                                                           MAIN      346
  467 RCOL = RCOL - RHOPP * FF * DIS                                     MAIN      347
      DISS = DISS - DIS * FF                                             MAIN      348
      IF(DISS .EQ. 0.0) GO TO 468                                        MAIN      349
      RHOPP = RCOL / DISS                                                MAIN      350
      GO TO 470                                                          MAIN      351
  468 RHOP = 0.0                                                         MAIN      352
  470 CONTINUE                                                           MAIN      353
      PRES = 0.5*RHOPP*RHOJ2*V2*V2/(SQRT(RHOPP)+SQRT(RHOJ2))**2          MAIN      354
C     WRITE(6,98) RHOPP, RHOJ2, V2                                       MAIN      355
      FP = 1.0 / (1.0+(SQRT(PRES/RHOJ2))/(ALPHA*V2))                     MAIN      356
      IF((AP*RHOAP+BP*RHOBP+CP*RHOCP) .EQ. 0.0) GO TO 474                MAIN      357
      Y2 = AK * E2 / (1.0+E2*RHOJ2/(AP*RHOAP+BP*RHOBP+CP*RHOCP))         MAIN      358
      GO TO 476                                                          MAIN      359
  474 Y2 = 0.0                                                           MAIN      360
  476 DELY2 = -Y2 * (1.0-SQRT((1.0+ALPHA*HP/E)/(1.0+ALPHA*FP*HP/E)))     MAIN      361
      P4 = 0.0                                                           MAIN      362
      DX = (AL-(DELL1+DELL1P+DELL2)) / 100.0                             MAIN      363
      X = 99.5 * DX                                                      MAIN      364
      DO 500 I = 1,99                                                    MAIN      365
      P4 = P4 + DX * (1.0+C1*CAPL/(1.0+C1*X))                            MAIN      366
      X = X - DX                                                         MAIN      367
      IF(P4 .GE. DELY2) GO TO 510                                        MAIN      368
  500 CONTINUE                                                           MAIN      369
  510 DELL2P = AL - (DELL1+DELL1P+DELL2) - X                             MAIN      370
C     WRITE(6,80) Y2, V2, PRES, F, DELY2, P4, DELL2P, FP                 MAIN      371
      PP = 0.0                                                           MAIN      372
      DX = AL - (DELL1+DELL1P+DELL2+DELL2P)                              MAIN      373
      DX = DX / 100.0                                                    MAIN      374
      X = DX / 2.0                                                       MAIN      375
      DO 600 I = 1,99                                                    MAIN      376
      IF(RHOZ .EQ. 0.0 .OR. RHOT .EQ. 0.0) GO TO 650                     MAIN      377
      PP = PP + (SQRT(RHOZ/RHOT)) * DX * (1.0+(C1*CAPL+C1*PP)/(1.0+C1*X) MAIN      378
     1)**0.5/(1.0+ALPHA*CAPL/E) ** 0.5                                   MAIN      379
      X = X + DX                                                         MAIN      380
  600 CONTINUE                                                           MAIN      381
      PPIN = PP / 2.54                                                   MAIN      382
  650 CONTINUE                                                           CORR8       6
      IF(C .GT. 2.0 .OR. PP .GT. 2.0) GO TO 655                          MAIN      384
      IPCC = IPCC + 1                                                    MAIN      385
      PLC(ICC) = C + CP * PLPP(ICC) = PP                                 CORR8       7
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  655 CONTINUE                                                          MAIN      388
      PLC(IPCC+1) = 0.0                                                 MAIN      389
      PLPP(IPCC+1) = 0.0                                                MAIN      390
      PLC(IPCC+2) = 0.2                                                 MAIN      391
      PLPP(IPCC+2) = 0.2                                                MAIN      392
      CALL LINE(PLC,PLPP,IPCC,1,0,0)                                    MAIN      393
  660 CONTINUE                                                          MAIN      394
      CALL PLTPGE                                                       MAIN      395
  670 CONTINUE                                                          MAIN      396
  680 CONTINUE                                                          MAIN      397
  700 CONTINUE                                                          MAIN      398
 3000 CONTINUE                                                          MAIN      399
      STOP                                                              MAIN      400
      END                                                               MAIN      401
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